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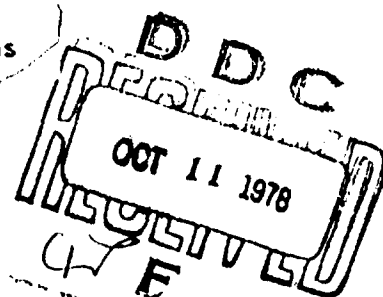
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**STUDY OF THE PERFORMANCE  
OF AIDS TO NAVIGATION  
SYSTEMS - PHASE I,  
AN EMPIRICAL MODEL  
APPROACH**

W. R. /Bertsche, A. J. /Pesch,  
J. L. /Masakasy, J. G. /Clark D. A. /Atkins



19 JUL 1978

**FINAL REPORT**

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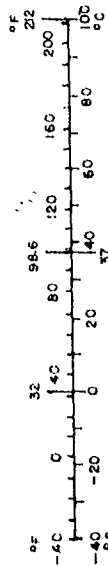
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
sq in	square inches	6.5	square centimeters	cm <sup>2</sup>
sq ft	square feet	0.09	square meters	m <sup>2</sup>
sq yd	square yards	0.8	square meters	m <sup>2</sup>
sq mi	square miles	2.6	square kilometers	km <sup>2</sup>
acre	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
oz	ounces	28	grams	g
lb	pounds	4.5	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
<b>VOLUME</b>				
fl oz	fluid ounces	30	milliliters	ml
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
cu ft	cubic feet	0.03	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5/9 after subtracting 32	Celsius temperature	°C

## Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	1.1	yards	yd
		0.6	miles	mi
<b>AREA</b>				
cm <sup>2</sup>	square centimeters	0.16	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	yd <sup>2</sup>
km <sup>2</sup>	square kilometers	0.4	square miles	mi <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	ac
<b>MASS (weight)</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
<b>VOLUME</b>				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m <sup>3</sup>	cubic meters	35	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.3	cubic yards	yd <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°C	Celsius temperature	9/5 then add 32	Fahrenheit temperature	°F



For more information on metric measures, see the Metric Handbook, published by the National Bureau of Standards, Gaithersburg, MD 20899.

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### MASTERS

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## CONTENTS

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
1	INTRODUCTION	1-1
	1.1 Key Tasks and Level of Accomplishment	1-1
	1.1.1 Application of At-Sea Data Bases	1-1
	1.1.2 Application of Pilot and Port Authority Knowledge	1-1
	1.1.3 Application of Simulator Data Bases	1-2
	1.1.4 Application of the Techniques of a Specialized Modeling Language	1-2
	1.2 An Encompassing Approach to the Problem	1-2
	1.3 Organization and Scope of the Report	1-3
2	REQUIREMENTS FOR AN AID TO NAVIGATION PERFORMANCE MODEL	2-1
	2.1 Observable Behavior and Measurable Performance Basis for Model Development	2-1
	2.2 Sensitivity of Measures of Effectiveness to Changes in AN Variables	2-3
	2.3 Measures of Effectiveness Indicating Relative Safety and Traffic Facilitation	2-4
	2.4 Validation of Model and Output Measures of Effectiveness	2-6
	2.5 Model Evaluation of Broad Range of Aids to Navigation in Diverse Geographic Regions	2-7
	2.6 Model Use at District and Washington Levels	2-8
3	DEFINITION AND VALIDATION OF AID TO NAVIGATION MEASURES OF EFFECTIVENESS	3-1
	3.1 Fix and Piloting Accuracy	3-1
	3.2 Navigating and Steering Accuracy	3-12
	3.3 Traffic Capacity	3-23

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
4	DESIGN AND USE OF AID TO NAVIGATION PERFORMANCE MODEL	4-1
4.1	Design Approach to Model Development	4-1
4.2	Equipment Error, Perceptual Differences, and Behavioral Response	4-3
4.2.1	Equipment Error	4-3
4.2.2	Human Perceptual Error	4-4
4.2.3	Behavioral Variations	4-8
4.3	Data Inputs	4-14
4.3.1	AN and RA Characteristics	4-14
4.3.2	Navigation Processes	4-18
4.3.3	Traffic Capacity	4-19
4.4	Operation of Models and Output Capabilities	4-19
4.4.1	Fix Model	4-19
4.4.2	Navigating and Steering Model	4-27
4.4.3	Traffic Capacity Model	4-36
5	DEMONSTRATION AND VALIDATION OF AID TO NAVIGATION PERFORMANCE MODELS	5-1
5.1	Introduction	5-1
5.2	Sensitivity of AN Performance Models to Changes in AN Configurations	5-1
5.2.1	Sensitivity of AN Model	5-1
5.2.2	Sensitivity of Navigating and Steering Model	5-6
5.2.3	Sensitivity of Traffic Capacity Model	5-13
5.3	Demonstrated Flexibility of the AN Performance Model	5-13
5.3.1	Sample Scenario Evaluations: Florida Keys	5-17
5.3.2	Sample Scenario Evaluation: Miah Mauli Range Channel, Delaware Bay	5-17
5.3.3	Sample Scenario Evaluation: CAORF Restricted Waterways	5-25
5.4	Model Validation	5-25
5.4.1	Validation of Visual Perception Fixing Routines	5-25
5.4.2	Validation of Entire Navigating and Steering Model	5-33
5.5	Overview of Model Capabilities and Achieved Goals	5-33

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
6	PLAN FOR COMPLETION, VALIDATION, AND APPLICATION OF THE AID TO NAVIGATION PERFORMANCE MODELS	6-1
6.1	Introduction	6-1
6.2	Phase II: AN Performance Model Development and Validation	6-1
6.2.1	Task 2.1. Complete Model Development and Validate	6-1
6.2.2	Task 2.2. Conduct CAORF - Restricted Waterways IV Experiment	6-3
6.2.3	Task 2.3. Collect Data At Sea	6-3
6.2.4	Task 2.4. Conduct Preliminary Investigation of AN and RA Requirements	6-3
6.2.5	Task 2.5. Conduct At-Sea Evaluation of a Selected Harbor	6-4
6.3	Phase III: Establishment of AN and RA Requirements and Harbor Evaluation	6-4
6.3.1	Task 3.1. Establish AN Performance Models at Coast Guard Headquarters.	6-4
6.3.2	Task 3.2. Establish Minimum AN and RA Requirements	6-4
6.3.3	Task 3.3. Evaluate Harbor with AN Performance Model and Project Improvements	6-4
6.3.4	Task 3.4. Verify Improvements to Selected Harbor on CAORF	6-5
6.4	Phase IV: Establishment of AN Performance Models at District Level and Validation of Harbor Improvements	6-5
6.4.1	Task 4.1. Update Model and Use Techniques Required	6-5
6.4.2	Task 4.2. Change AN and Verify Improvements in Harbor	6-5
6.4.3	Task 4.3. Establish AN Performance Models at Coast Guard District Offices	6-5
6.5	USCG Workshops	6-5
6.6	Risk Associated With Conducting Phase II, III, and IV Work	6-6
REFERENCES		R-1

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
APPENDICES		
APPENDIX A	Technical Description of Models	A-1
APPENDIX B	Mariner's Requirements for, and Information Obtained from AN	B-1
APPENDIX C	At-Sea Data Collection	C-1
APPENDIX D	Suggested AN Study Areas for New York Harbor	D-1
APPENDIX E	Simulator Research Facilities Review	E-1

## FIGURES

<u>NO.</u>	<u>TITLE</u>	<u>PAGE</u>
3-1	Cross and Along Track Standard Deviations in Pilot's Static Estimated Position Approaching Different AN Configurations (Data Collected at CAORF)	3-3
3-2	Cross and Along Track Standard Deviations in Pilot's Static Estimated Position as a Function of Additional Buoys Along Channel (Data Collected at CAORF)	3-4
3-3	Cross and Along Track Standard Deviations in Pilot's Static Estimated Position Versus Distance to Gated Buoys (Data Collected at CAORF)	3-5
3-4	Cross and Along Track Standard Deviations in Pilot's Static and Dynamic Estimated Position (Data Collected at CAORF)	3-7
3-5	Fix Accuracy Versus AN Configuration (Eclectech At-Sea Data Base)	3-8
3-6	Fix Accuracy/Hazard Distance Ratio Versus AN Configurations (Eclectech At-Sea Data Base)	3-9
3-7	Fix Accuracy Versus AN Configuration (CAORF Restricted Waterways Data)	3-10
3-8	Fix Accuracy/Hazard Distance Ratio Versus AN Configuration (CAORF Restricted Waterways Data)	3-11
3-9	Ship Track Recorded, Straight Channel	3-13
3-10	Swept Path Widths in Southampton Water	3-14
3-11	General Differences of Track Between Inbound and Outbound VLCCs	3-16
3-12	Pilot Waters, Maneuvering Strategies	3-17
3-13	Swept Width Probability Functions Versus AN Configurations (Eclectech At-Sea Data Base)	3-18
3-14	Swept Width Probability Functions Versus AN Configurations for CAORF Restricted Waterways	3-19
3-15	Differences in Swept Width Between Use of Radar Alone and Radar with Navigation and Information	3-21
3-16	Swept Width Probability Functions Versus AN Configurations at Time of CPA to Traffic Vessels (CAORF Restricted Waterways)	3-22
3-17	Route Identification for Sandy Hook (24 Hours of Coverage Plotted Every Half Hour, Tuesday, 12 February 1974)	3-25

<u>NO.</u>	<u>TITLE</u>	<u>PAGE</u>
3-18	Time of Day (Hours) Radar Vessel Density Data	3-26
3-19	Radar Vessel Speed Data - Port of New York	3-27
4-1	AN Performance Models	4-2
4-2	Visual Bearing Error, Mean Displacement Function, Single Buoy (CAORF Data)	4-9
4-3	Visual Bearing Error, Standard Deviation Function, Single Buoy (CAORF Data)	4-10
4-4	Visual Range Error, Mean Displacement Function, Single Buoy (CAORF Data)	4-11
4-5	Visual Range Error, Mean Displacement Function, Single Buoy (CAORF Data)	4-12
4-6	Distribution of Time to Complete Maneuver for a 2-Degree Course Change	4-13
4-7	Average Time to Complete Maneuvers Versus Course Change	4-15
4-8	Distribution of Maneuvering Orders	4-16
4-9	Estimated Position at Issuance of Orders	4-17
4-10	Fix as Independent and Dependent Observations	4-21
4-11	Relationship of Vertical and Horizontal Visual Angles for Ranges and Buoys	4-22
4-12	Output Data Sheet for Fix Model A	4-24
4-13	Cross Track Position Relative to Eight ANs	4-25
4-14	Cross Track Standard Deviation for Fix Accuracies Calculated Along the Track	4-26
4-15	Distributions in Maneuvering Model	4-28
4-16	Synthesis of Multiple Scenarios	4-30
4-17	Actual Head Plot	4-32
4-18	Ordered Head Plot	4-33
4-19	Rudder Angle Plot	4-34
4-20	Variance X-Track Plot	4-35



<u>NO.</u>	<u>TITLE</u>	<u>PAGE</u>
4-21	Heading Response Plot	4-37
4-22	Rudder Response Plot	4-38
4-23	Ship Center of Gravity Plot	4-39
4-24	Cumulative Swept Width Function	4-40
4-25	Probability Density Function and Cumulative Function for Cross Track Position	4-41
4-26	Model Representation of Traffic Flow	4-42
4-27	Traffic Capacity Model - Monte Carlo	4-44
4-28	CRT Display Output for the Traffic Model	4-46
4-29	Listing Output for the Traffic Model	4-46
4-30	Ship Delay Times Plotted by the Traffic Model	4-47
5-1	Tracking for Fix Information, Buoy Spacing $3/4$ Nautical Mile	5-2
5-2	Cross Track Fix Standard Deviation Along Track, Buoy Spacing $3/4$ Nautical Mile	5-3
5-3	Tracking for Fix Information, Buoy Spacing $1-1/2$ Nautical Miles	5-4
5-4	Cross Track Fix Standard Deviation Along Track, Buoy Spacing $1-1/2$ Nautical Miles	5-5
5-5	$1/2$ -Mile Visibility, Buoy Spacing $3/4$ Mile	5-7
5-6	$1/2$ -Mile Visibility, Buoy Spacing $1-1/2$ Miles	5-8
5-7	Track Plots, Four Monte Carlo Cases, Clear Visibility	5-9
5-8	Accumulated Swept Width Data for Alternate AN Configurations, Clear Visibility	5-10
5-9	Track Plots, Four Monte Carlo Cases, $1/2$ -Nautical Mile Visibility	5-11
5-10	Accumulated Swept Width Data for Alternate AN Configurations, $1/2$ -Nautical Mile Visibility	5-12
5-11	Traffic Restrictions in a Straight Channel	5-14
5-12	Vessel Delay Times With Passing Restrictions	5-15

<u>NO.</u>	<u>TITLE</u>	<u>PAGE</u>
5-13	Vessel Delay Times Without Passing Restrictions	5-16
5-14	Sample Scenario Evaluation, Florida Keys	5-18
5-15	Computer Listing of Data Base	5-19
5-16	Track Curves for Three Monte Carlo Runs, Florida Keys	5-20
5-17	Miah Maull Range Channel, Delaware Bay	5-21
5-18	Track Plots for Miah Maull Range Channel Scenario	5-22
5-19	Cumulative Swept Width Model Data in Miah Maull Range	5-23
5-20	Cumulative Swept Width for a Single Track Recorded During At-Sea Data Collection	5-24
5-21	CAORF Restricted Waterways Channel	5-26
5-22	Track Plots for CAORF Restricted Waterways	5-27
5-23	Accumulated Swept Width Data for Restricted Waterways Channel, Model Data Versus CAORF Data, Cutoff Turns with Mid-Leg Buoys	
5-24	Validation of Visual Fix Estimation, CAORF Restricted Waterways Channel, Cutoff Corner with Mid-Leg Buoys	5-30
5-25	Validation of Visual Fix Estimation, CAORF Restricted Waterways Channel, Cutoff Corner Without Mid-Leg Buoys	5-31
5-26	Comparison of Random Model Fixes with Performance of CAORF Subject Group	5-32
6-1	Plan for Completion, Validation, and Application of AN Performance Models	6-2

#### TABLES

3-1	Per Diem Costs of Operating Commercial Vessels and Maneuvering Speeds	3-23
4-1	Equipment Errors	4-5
4-2	Mean Values for Navigation Perceptual Task	4-6
4-3	Standard Deviation of Distributions About the Mean Values for Navigation Perceptual Tasks	4-7

## Section I

### INTRODUCTION

This report presents the results of a Phase I investigation concerned with establishing the feasibility of developing a systematic approach through which the effectiveness of alternate aid to navigation (AN) systems can be determined. The three-faceted approach developed by Eclectech Associates (EA) consists of selectively combining at-sea data, simulator data, and a fast time Monte Carlo model to detail the parameters of the navigation process and to yield the desired measures of effectiveness. The approach may be characterized as a "modeling process," which draws from several disciplines and sources to achieve a balanced end result, not solely dependent on one area of expertise. To ascertain whether the multifaceted approach selected is both valid and highly feasible, EA proceeded beyond the design stage of Phase I into the development and preliminary validation of the approach in each of its three major facets. Data are presented herein to establish the success of this effort.

#### 1.1 KEY TASKS AND LEVEL OF ACCOMPLISHMENT

The extent of progress was possible as a function of our ability to capitalize on prior data and knowledge in each of these areas. The effort as proposed in Phase I was based on the contention that EA could proceed expeditiously and factually in several key tasks. These tasks and our levels of accomplishment are briefly outlined below.

##### 1.1.1 Application of At-Sea Data Bases

The effort proposed to examine and utilize previously collected at-sea data bases, which describe the navigation process in terms of the mariner's behavior as a function of the marine environment. We also proposed to collect additional data at sea specifically oriented to quantifying the accuracy of a pilot's ability to navigate as a function of particular AN systems. We utilized the existing data to develop a modeling structure and to define specific examples of the navigation process. We also demonstrated the ability to gather data at sea through which we refined this structure and importantly demonstrated the application of these data as input to a fast time computer model. These data also were applied in the demonstration of the iterative modeling process where they serve as a validity measure of the fast time model's ability to produce accurate predictions of a pilot's behavior.

##### 1.1.2 Application of Pilot and Port Authority Knowledge

The effort proposed to utilize the knowledge of pilots and port authorities, on a world-wide basis, to glean data from which a pragmatic foundation for the modeling process could be established. Detailed data were gathered in the major ports of Europe and along the East Coast of the United States. The approaches to and channels of New York Harbor were reviewed in detail to establish target questions for model application. These data were compared to at-sea and simulator data of pilot performance to separate opinion from actual performance. This task led to the definition of structure for modeling the pilot's behavior, which could only be determined from the removal of bias and confirmation of key behaviors.

### 1.1.3 Application of Simulator Data Bases

A basic assumption in the approach was that bridge simulators designed for research (such as CAORF)<sup>1</sup> and laboratory systems operating at EA would provide valid data for input to the modeling process. During the course of Phase I, the USCG conducted a program at CAORF in combination with an ongoing MARAD experiment. EA analyzed these data as they were made available by the USCG and MARAD and applied them to the development of the modeling process. The data provided:

- a. input as distributions of pilot behavior to the fast time computer model.
- b. validation of the model's ability to interpolate and extrapolate pilot and ship behaviors between and beyond the CAORF data.
- c. a comparison and validity check to at-sea data.

Importantly, the procedures through which to utilize CAORF data in the modeling process were successfully demonstrated.

### 1.1.4 Application of the Techniques of a Specialized Modeling Language

Another basic assumption was that the experience and modeling techniques which exist in a specialized modeling language, developed for similar Monte Carlo man in the loop models, could be profitably applied to this problem. This was demonstrated in this phase by developing a specialized AN modeling language. The model was applied at its current stage of development to AN scenarios and compared to CAORF and at-sea data with favorable results. The modeling language was designed for use by nonprogrammer personnel through the use of English language-like statements. It was also specifically designed as a highly flexible approach to the modeling process, since its logic, data distributions, and output are all externally defined. These inputs originate primarily in the other two areas of the modeling process: at-sea and simulator data. Inputs are also defined from other sources such as human factors laboratory data, empirical research findings, equipment characteristics, and environmental effects.

Our point in reviewing these key tasks is to illustrate that we have proceeded as we originally envisioned and have demonstrated the feasibility of each task through actual accomplishments.

## 1.2 AN ENCOMPASSING APPROACH TO THE PROBLEM

The approach to the problem was selected on the basis of the ability to produce results acceptable and valid in the maritime community. This necessarily resulted in a reasonably complex solution when viewed in detail. The approach is multifaceted and does not rely therefore on a single discipline or set of techniques to solve the problem. Rather it is designed to produce results both iteratively through development of data at sea, in simulators, and from fast time models, and singly from each of these areas.

---

<sup>1</sup>CAORF - Computer Aided Operations Research Facility, Maritime Administration, Kings Point, Long Island, New York

Alternate approaches were viewed as resulting in short-term results having relatively narrow applicability to the total AN problem. For example, models of the human operator have had a history of resulting in successfully describing functions which, when applied to real world unconstrained problems, only result in large unexplained remnant terms. One has only to review the twenty years of development of human operator models that describe aircraft pilot behavior to see the shortcomings of this approach. These describing functions also primarily deal with psychomotor skills and have not addressed the cognitive functions applied by maritime pilots. Other approaches have not been totally disregarded. For example psychophysical measurements and certain describing functions may find applicability in selected areas as input distributions for the fast time models. The problem is that if these approaches were the prime area of concentration, extensive data collection would be necessary without any guarantee that the results were applicable to at-sea conditions.

For this reason our approach begins with the pilot's behavior as measured at sea and in simulators and attempts to model and develop explicit relationships which can be continuously validated to the real world. This is achieved through a systematic series of checks and balances. We recognized that this encompassing approach would be viewed as difficult to achieve; we therefore directed our efforts during Phase I to proving the feasibility in each area and that data could be collectively expanded and validated by iteration through each area. It remains our belief that this problem must be approached in this manner to achieve results which will be valid and accepted in the maritime field.

### 1.3 ORGANIZATION AND SCOPE OF THE REPORT

This report has been written at a level commensurate with the current stage of development. This means we have concentrated on describing the overall requirements, the measures of effectiveness, the model itself, and most importantly, the validity of the modeling process. This can be demonstrated at this time through comparison runs of at-sea, simulator, and model data. Details of the model along with specific items required by contract in Phase I may be found in the Appendices. We have avoided presenting the extensive detailed mathematical descriptions, computer program listings, and modeling techniques in the main body of the text, since they refer to an earlier stage of development and would only serve to burden the reader interested in examining the validity and feasibility of our approach to solving the AN problem. The model is operating at EA and is available along with program listings, and detailed model design documentation in a less formal document. The reader is urged to study the various figures and tables of the report, since we have attempted to concentrate the thrust of our findings in this format.

## Section 2

### REQUIREMENTS FOR AN AID TO NAVIGATION PERFORMANCE MODEL

In our approach to the design of an aid to navigation (AN) performance model, we established specific requirements to (1) meet the needs of the USCG AN branches (Coast Guard Headquarters and district offices) and (2) provide a methodology that would permit model output to be easily validated against at-sea navigator performance as a function of aids to navigation. Model design incorporated these requirements as well as flexibility and user simplicity. Specific requirements for the model were to:

- a. Base model development on observable behavior and measurable performance recorded at sea and on ship simulators.
- b. Provide output measures of effectiveness sensitive to changes in AN variables.
- c. Provide output measures of effectiveness that adequately indicate relative safety and traffic facilitation.
- d. Include validation of the model and its output measures of effectiveness as an implicit part of the model development process.
- e. Design a model capable of evaluating performance of a broad range of ANs in diverse geographic regions.
- f. Design a model simple enough for use in AN selection and placement at the district office level, yet sophisticated enough to be used as a valuable research tool at USCG branches in Coast Guard Headquarters.

We met each of these requirements including validation of the operation of the initial models. The following paragraphs describe these requirements for the models developed and used during this effort.

#### 2.1. OBSERVABLE BEHAVIOR AND MEASURABLE PERFORMANCE AS BASIS FOR MODEL DEVELOPMENT

Our approach focused on developing a model on behavioral performance data observed and measured at sea or in validated ship simulators. Our experience in analyzing the performance and behavior of merchant marine deck officers both at sea and on ship simulators was the basis for the design of our model. In the past, deck officer behavior has been studied via interview, operational sequence diagrams, job requirements studies, and personal opinions (references 1 through 5). These studies often recommend methods of navigating, piloting, and steering ships, but because the investigators do not gather data at sea, the studies fail to document what actually occurs at sea.

In contrast to this approach, personnel from Eclectech Associates rode a large number of commercial ships in various geographic areas during a study sponsored by MARAD (reference 6). The sole purpose of this study was to observe and document routine deck officer behavior and performance during all conditions of traffic with a variety of navigational aids. The data obtained from this study, subsequently computer coded and analyzed, formed a quantified, statistically valid data base of deck officer behavior and performance. A comparison of this data to previous studies indicated that

behavior at sea was very often not what had been stated in interviews or hypothesized in job requirement studies. Specifically, the use of AN, fix frequency, and fix methods differed widely from those hypothesized, or the behavior hypothesized was so general that it could not be applied to a specific set of ANs observed at sea.

Although we believe that data collection at sea is mandatory for the ultimate validation of any AN model, it must be recognized that all conditions cannot be controlled at sea and that a great deal of data must be collected to establish a valid statistical sample. Therefore, we recognize data collection on such validated ship simulators as CAORF as a partner to at-sea data collection. This unique facility dynamically simulates visual and radar images and traffic, landmass, and environmental effects, all fully variable and controlled through computer programming. (See Appendix E).

Our own experience with this facility is extensive. We used our at-sea data bases for validation of the facility and participated in the following programs as principal investigators, data analysts, or marine advisors:

- CAORF Validation Program (Reference 7)
- Collision Avoidance Study (Reference 8)
- Valdez Operational Exercises (Reference 9)
- USCG Rules of the Road Experiment (Reference 10)
- USCG Training Requirements (Reference 11)
- USCG Restricted Waterways Experiment IIIB (Reference 12)
- Upcoming Restricted Waterways Collision Avoidance Study (Reference 13).

It would be incorrect to say that the behavior and performance of pilots, mates, and masters on CAORF equaled at-sea behavior and performance, since minor differences have been noted in validation studies. However, it is correct to say that major performance variations have been equivalent between at-sea data bases and simulator data bases; CAORF thus provides a facility for interpolating and extrapolating data points and behavior between and beyond equivalent at-sea data bases. To the extent that CAORF does duplicate at-sea conditions, all data observable and measurable at sea can be observed and measured on CAORF. CAORF provides the added convenience of complete recording of ownship position and attitude data throughout experimental runs; similar data collection at sea usually demands sophisticated and expensive electronic equipment.

The objective nature of data collection is the key to valid at-sea and ship simulator data bases. The data compiled is mostly observed and measured with minimal contact with pilots, masters, and mates. Based on our experience, questioning deck officers during performance of their duties often invalidates the process being observed and thus destroys the usefulness of the data. Therefore, our data bases are composed of observed events and measured performance and represent real behavior. The single exception to this occurs in that part of the at-sea piloting data base compiled for this report wherein we tried to measure the difference between the ship's actual position and the pilot's estimated position. Pilots were asked in preselected sections of the channel to estimate the ship's position. This question alone often caused the pilot to look specifically to range lights or the radar when he would have otherwise taken no action. This behavior was specifically noticeable if he picked up binoculars to sight a distant range or stepped out of the wheelhouse to sight a range aft. During this process we carefully noted the pilot's position estimate before and after looking to the ANs.

The AN performance models developed under this program were designed around and validated against the observed behavior and measured performance of our at-sea and CAORF simulator data bases accessible to us. The data base compiled under the MARAD program was used to provide AN model input data for navigation in coastal waters, port approaches, harbor confluence areas, and harbor waterways. This data was augmented by conducting an additional at-sea data collection during development of our AN models for this contract. The specific goal of this data collection was to begin to compile a data base representative of pilot's use of ANs in harbor waterways. Section 3 and Appendix C discuss the scope of these two data bases and their specific input to the AN model development.

## **2.2. SENSITIVITY OF MEASURES OF EFFECTIVENESS TO CHANGES IN AN VARIABLES**

The AN performance model will be used primarily to study the effects of varying certain AN characteristics and deployment criteria so that an effective tradeoff can be made between cost, efficiency, and safety. Selecting appropriate AN configurations or establishing general AN deployment criteria requires that the AN model receives as input data the exact variables the USCG wishes to evaluate and, further, that the output measures of effectiveness be sufficiently sensitive to AN variables for a tradeoff to be successful. AN variables considered of interest include as a minimum:

- AN reliability
- Placement (lateral or cardinal)
- Type (fixed or floating)
- Detection range (day and night)
  - Size
  - Light intensity
  - Color
  - Contrast
  - Angular light band
  - Radar reflectance
  - Flash type
- Placement accuracy
- Radio aid accuracy

Three measures of effectiveness that can be shown to be sensitive to these variables are:

- a. fix and piloting accuracy,
- b. navigating and steering accuracy, and
- c. traffic capacity

The first of these measures, fix and piloting accuracy, represents the probability of error in position that may result during the application of normal fixing and piloting processes. Such errors result from both equipment inaccuracies and human error functions in interpreting equipment readings or visual information. Changes in AN placement,



detection range, reliability, etc, have been shown to affect the value of this error. Examples of data which support this are given in Section 3.1 of this report.

The second measure of effectiveness, navigating and steering accuracy, is a measure of the cross channel width the ship requires to maneuver given a specific configuration of AN and potential for making an error in position estimation. This band is necessarily wider than the fix error band as a function of varying ship control capability of the pilots, masters, and mates, and varying skill levels of the helmsman. This measure has been shown to be sensitive to changes in AN variables. Examples of data supporting this are discussed in Section 3.2.

The third measure of effectiveness of ANs is traffic capacity. This measure represents conditions met when the channels are crowded and vessels are slowed in their transiting or are required to wait to enter the port or leave their berth. Judicial placement of ANs may allow more accurate ship piloting in critical areas to aid passings in certain areas previously considered unsuitable for passing. Data indicating a change in passing behavior as a function of AN variables are discussed in Section 3.3.

All three measures of effectiveness discussed above meet the requirement of Section 2.1 in that they are measurable performance indicators both at sea and in ship simulators.

## 2.3. MEASURES OF EFFECTIVENESS INDICATING RELATIVE SAFETY AND TRAFFIC FACILITATION

ANs must contribute to safe and quick navigation, piloting, and steering of ships from one area to another. This is the ultimate measure of AN effectiveness. Safety, to the extent that it represents risk of collision or grounding, provides a measure of the amount of life and environmental protection afforded by aids to navigation.

An obvious method of representing safety would be quantification of the relationship between ANs and the probability of collision or grounding. Our own assessment of quantifying such probabilities and review of a number of analytical studies of marine accidents (references 6 and 14 through 17) yielded the conclusion that insufficient (and in part inaccurate or questionable) data are available across a large enough sample of accidents to develop an accurate relationship. Further, if formulating such a relationship were possible, it would be impractical to verify and test that it was correct from observation of real world accidents. The relatively low probability of accidents would require a very large sample size to validate the relationship.

An alternate approach to determining the probability of accidents is to determine indirect measures of safety observable in master, mate, and pilot behavior and in ship's responses. We have been relatively successful (reference 6) in identifying observable behavior and measurable performance indicative of the relative probability of collision. We were able to show in our at-sea data bases, with statistical reliability, that use of collision avoidance systems versus radar reflection plotting doubled or tripled the range at which ownship detected collision threats, doubled the range at which ownship initiated evasive maneuvers, and doubled CPAs (closest points of approach) when ownship maneuvered from privileged ships. The extent to which collision avoidance systems reduce the probability of collision is presently unknown and will not be quantified from accident data for years to come. Over 600 collision avoidance systems have been deployed at sea during the past 10 years, and there has yet to be a major collision involving a ship using the systems. For ship operators and agencies wishing to make a decision on whether or not to install collision avoidance systems, our measures of

effectiveness recorded at sea (threat detection range, maneuvering practices, and resultant CPA)<sup>2</sup> provide a practical and observable indication that increased safety is provided by the systems.

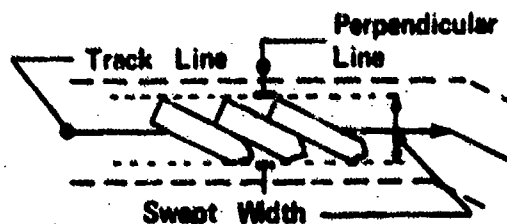
Applying collision avoidance measures of effectiveness described above to evaluation of AN would be unsatisfactory; generally, they lack the fine gradation of measurement and direct relation to safety required for AN evaluation. Nevertheless, applying other measures of effectiveness that are observable and measurable at sea is possible. To the extent we can measure positions estimated by masters, mates, or pilots using short and long range ANs, the distribution of the error in their estimates versus actual position provides one measure of relative safety. Should this distribution of error on or about a navigational hazard (e.g., shallow water) fall in both safe and hazardous water, there then exists a probability that a navigator can actually ground on that hazard while estimating his position to be in safe water. Practically speaking, our interest lies in the navigator's ability to estimate that he is in safe navigable water or approaching hazardous waters and concurrently exercise steering control to keep the vessel in safe waters.

The distribution of error in estimated position does not necessarily represent a measure of safety provided by ANs. Given different crews and ships of different size and controllability, the distribution of maneuvering room required (width of channel) will be different. There exists an additional measure of effectiveness representing the relative safety of specific ships navigating with specific ANs. This is the swept width<sup>3</sup> density function which can be measured at sea. This particular function is shown in Section 3.2 to contain the probability of the hull excursions outside a channel of safe navigable waters. Given data on sufficient vessel transits, this measure approaches describing the probability of grounding or inadvertently crowding oncoming traffic by crossing the centerline. There must be sufficient numbers of transits included in the data to establish a statistically reliable distribution of swept width along those portions of the channel being investigated. The actual interval chosen along the channel will depend on the channel characteristics and will vary from area to area, but once chosen, will remain constant for evaluation of alternate AN configurations. Since the probability of grounding or collision is of primary interest relative to safety, it is seen that the distribution of swept width will provide a yardstick for safety against which alternate AN configurations can be measured.

Measures of effectiveness representative of traffic facilitation are intrinsically linked to the measures relative to safety. Alternate AN configuration may permit vessels to navigate safely at higher speeds, thus aiding the movement of vessels through navigable waters. Alternate AN configurations may also permit more accurate maneuvering in narrow channels so that ships may safely pass more frequently. Both of these effects are ultimately represented in a measure of the delay relative to average passage time while traveling from one point to another. A measure of effectiveness of traffic facilitation on a micro scale would be average ship speed along particular channels. A measure of

<sup>2</sup> A number of other measures of effectiveness associated with the deck officer's average and peak workloads also improved dramatically with the use of collision avoidance systems. Such measures, however are less applicable to AN evaluation (reference 6).

<sup>3</sup> Swept width is defined as the distance that the hull of a vessel, at the waterline, "cuts out" of a line perpendicular to the track line.



effectiveness of traffic facilitation on a macro scale is average delay in arrival or departure within a channel system or harbor. Measures of delay of specific ships may be directly related to the additional cost of operating ships. Commercial ship operators are universally concerned with minimizing costs in port and maximizing returns while crossing open seas.

All three measures of effectiveness selected for the AN performance model are observable and sensitive to changes in AN variables and adequately indicate relative safety and traffic facilitation provided by particular AN configurations. A more detailed discussion of the exact definition of these measures of effectiveness and examples of these variables observed at sea and on simulators are given in Section 3.

#### 2.4. VALIDATION OF MODEL AND OUTPUT MEASURES OF EFFECTIVENESS

Because we recognized that an AN performance model had to represent the real world, we continually validated the model during the development process. We strove to design a model that represented the processes and behavior we had observed and documented at sea. Where key data were missing, we initiated further data collection both at sea and on CAORF. To aid validation of the model, we designed the model to accept documented behavior distributions as input data. Through internal adjustments to the logic coefficient and threshold values, we were thus able to achieve a match between the model's output measures of effectiveness and similar measures observed or measured at sea or on simulators.

There are two basic approaches by which the validity of a model can be ascertained. The first approach is to develop the model functions based on a portion of available data and then to demonstrate the model's ability to predict data which have not contributed to the modeling effort. This procedure, indicating an ability to predict behavior, is attractive for validating processes which are principally controlled by purely analytical relationships (e.g., ship hull model tests and response of ships to waves). It fails to deal with the high level of variability evident in human perception and decision processes. A second method of validation more attractive to human model is to refine the model to a point where a statistical match is produced at a selected level of confidence between the model output and measured data over a range of parameter values. The model can then be said to be valid within the range of the parameter values tested. Parameters considered for this task include factors such as type of AN, spacing and pattern of buoys, channel width, and visibility range. If the parameters and the range of parameter values are chosen carefully, the model validation will encompass the range of performance that interests the Coast Guard. Carefully devised CAORF experiments and at-sea data projects can provide measured data on those parameters which are significant over a broad range of values (navigation conditions). The model can then be validated over this same range of conditions. Within the stated parameter ranges, validity is nearly assured, since comparison of the model output and measured data will indicate any further need for refinement or tuning. The broad tuning ability within the Monte Carlo model and the ability to define the pilots' perceptive and responsive behavior through logical input provide assurance that statistically supportable matches to measured data can be made. Comparisons used to establish initial model validity are discussed in Section 5.

The continued compilation of at-sea and ship simulator data bases for model input and validation guarantees to the USCG that the model's internal operation and measures of effectiveness are valid indicators of the navigational process and AN performance. To the extent these data bases are descriptive of AN performance at sea today, they are themselves a valuable product of our AN model development.

## 2.5. MODEL EVALUATION OF BROAD RANGE OF AIDS TO NAVIGATION IN DIVERSE GEOGRAPHIC REGIONS

The USCG has a large inventory of ANs that are located in a wide range of geographic regions. Yet performance of any one or group of ANs in a particular geographic region must be evaluated by the AN performance model. Geographic regions which must be investigated include near coastal restricted waters, port approaches, channels in open waters, channels confined by land, and river channels.

Aids to navigation to be considered include floating aids (lighted and unlighted), fixed day marks, fixed lights, ranges, sectorized lights, radio aids (hyperbolic and omnidirectional), and VHF communications. Added to all the possible combinations of these variables are the different ship types and personnel who navigate and pilot these ships. Ships range in size from VLCC to small recreational craft. Ship navigators include U.S. and foreign masters and mates, federal pilots, state pilots, and owners of small commercial and recreational vessels. The skill levels of these groups and their knowledge of the local area vary widely. Appendix B discusses the differences between these variables. The range of differences in these variables required that the AN performance model feature a simple method to change any of the variables mentioned above.

This feature was realized in the AN performance model. The particular modeling technique used was to provide generalized sets of equations and subroutines that could be made to represent a specific set of variables by inputting coefficients, distributions, and subroutines. For example, a generalized set of hydrodynamic equations was programmed; "modeling" a specific ship type is obtained by inputting a list of coefficients for the various terms in the general equations. Simplicity of variable selection is achieved by prerecording coefficients for all the variables; the model user need only select a specific set of variables, and the proper set of coefficients will be automatically loaded. These coefficients are presently available for tankers, an LNG ship, a container ship and a mariner class general cargo ship. The deadweight capacity of these ships ranges from a low of 13,000 tons for the mariner to a selection of tanker sizes from 40,000 tons to 500,000 tons.

At this time, the model's input coefficients are prerecorded to allow evaluation of all ANs and RAs in coastal waters, port approaches, channels in open waters, and channels in confined waters. A wide range of vessel coefficients is available for evaluation of many vessel types in any of these areas. Navigational, piloting, and steering behavior coefficients and subroutines will be prerecorded for masters, mates, pilots, helmsmen, and recreational vessel captains as appropriate for specific geographic regions and ANs.

Prerecorded input coefficients will not necessarily limit the USCG to evaluation of only those input variables provided. In the next stage of model development, a syntax translator is planned which will allow the model user to build, improve, or customize any variable configuration or behavioral profile he wishes to evaluate. The user will input his changes or his entire scenario in an English language context; the syntax translator will automatically determine the proper coefficients and subroutines for loading in the generalized equations. (For prototype model evaluation in this effort, coefficients were determined manually and loaded automatically from data matrices.)

Our model has the flexibility of evaluating new variables or modifying prerecorded ones through the use of the syntax translator; this ensures vitality in its application to existing and future AN evaluation programs and guarantees that validity of the model can be maintained. Proper validation of the AN performance models across all variables of interest to the USCG will require compiling a more extensive at-sea and ship simulator

data base than currently exists. As these data become available, it will be possible to refine the initial input coefficients and to input more accurate distributions of observed behavior. The syntax translator allows such modifications to be made without major reprogramming of the model. To the extent that future ANs provide positional information to ships, new concepts in AN design, either visual or electronic, can be tested by restructuring variables and decision routines through the syntax translator.

## 2.6 MODEL USE AT DISTRICT AND WASHINGTON LEVELS

AN performance is of interest to administrative personnel at Coast Guard Headquarters and to operational personnel at the various district offices. At Headquarters, policy and budgetary decisions must be made which control deployment practices and funds for existing ANs and development funds for new ANs and RAs. AN performance evaluation and basic research are also conducted or directed by Coast Guard Headquarters.

At the district level the problem becomes pragmatic when a new AN is to be deployed. District personnel must select an appropriate AN design from the Coast Guard inventory and determine the best location for the aid. The problem is often deciding whether or not to discontinue an AN in a specific location. Although port authorities and pilot associations are usually consulted, the decision is made unilaterally.

It is clear that the AN performance model must work at the administrative, research, and operational levels. The model was structured for this variety of applications during the model development process.

One simplifying feature of the model is the use of prerecorded data and coefficients; these would be used selectively to represent a wide variety of geographic locations, ships, and ship's personnel. The user need not know the specifics of these routines to structure the program for his particular problem. Of course, he would be given full control of selecting and placing ANs in a geographic area he defines. The model would operate at the district office level in this mode. A more sophisticated use of the model is to use the syntax translator, previously described, to build a unique problem to study either research purpose questions or general AN deployment criteria. The model would be expected to operate at the Coast Guard Headquarters in this mode.

A third option for operation is to use only parts of the model at either the district or headquarters level. During model development we demonstrated that a model devoted solely to the measure of fix and piloting accuracy could be accommodated in a desktop computer. Although not all measures of effectiveness would be available in this model, its operation would be relatively fast and simple, thus allowing a large number of AN options to be traded off using fix and piloting accuracy as a measure of effectiveness.

Experience and user experimentation will ultimately determine how the models are used by the district offices and headquarters. Our goal in model development was to plan for and accommodate a wide variety of users and interest groups.

### Section 3

## DEFINITION AND VALIDATION OF AID TO NAVIGATION MEASURES OF EFFECTIVENESS

Three measures of effectiveness have been selected as output functions of the AN models. These are:

- a. fix and piloting accuracy,
- b. navigating and steering accuracy, and
- c. traffic capacity.

All three meet the requirements that they: be observable and measurable in the real world or on ship simulators; are sensitive to changes in aids to navigation; and provide a relative indication of safety and traffic effectiveness. This section defines each of these measures of effectiveness and presents data which prove the output functions meet the stated requirements.

### 3.1. FIX AND PILOTING ACCURACY

Fix and piloting accuracy is a measure of the ability of a master or mate in open sea or a pilot in confined waters to estimate his exact position. For a single fix it may be the distance between the officer's estimated position and the actual position. For large numbers of samples taken at the same actual position, fix accuracy can be represented as a probability distribution. The distribution of probabilities about the actual ship's position may not necessarily be a zero mean distribution (i.e., the mean of all estimated positions may not be the actual position); the statistical distribution of estimated positions is not necessarily Gaussian.

A two-axis representation of fix and piloting accuracy provides the simplest reference system for expressing accuracy. One axis is in the cross track; the other, in the along track direction. Accuracy may be represented as a mean displacement and a standard deviation along these respective axes. Position accuracy can also be indicated as a ratio of position error divided by the distance to the nearest hazard along these axes. This latter measure, empirically based, was used to evaluate piloting accuracy observed at sea. This ratio appears to provide an indication of relative safety.

A third method of representing piloting accuracy is to draw a map of the probabilities that describe the estimation of the ship to be at or near actual ship position. This method has the advantage of displaying the nonlinearities and skewness of the distribution which are not readily apparent from an observation solely of means and standard deviations. The AN performance models developed for this effort produce fix accuracy data in either the mean and standard deviation format or in a two-dimensional map showing the probability that estimated positions are other than the actual position. A ratio of error divided by distance to the nearest hazard can also be calculated by the models with minor modification to our current program. Examples of the output of the fix and piloting model are given in Section 5, Validation of AN Performance Models. Examples of these measures observed at sea and on simulators follow.

Selecting fix accuracy as a measure of effectiveness was initially based on hypothesized relationships and later verified by data collected on the CAORF simulator and at sea. Data are now available from the MARAD and USCG restricted waterways experiments at CAORF; these data provide a statistical representation of position estimation by nine pilots placed at identical points in channels with various aids to navigation. During a data collection trip from Providence, Rhode Island, to Philadelphia, Pennsylvania, we demonstrated that it was possible to measure the accuracy of a pilot's estimated position while negotiating channels.

The majority of the estimated fix data collected at CAORF represents a pilot's ability to estimate ship position with the ship stopped at a particular point in the channel. We define this to be their "static" fixing ability. During one session, the ship was steered at 6 knots through a channel with buoys. The pilots were asked to estimate their position at specified distances along the channel without stopping the ship. In this case the pilots had the advantage of estimating their current position knowing where they had been, their speed, and their direction. We define this to be their "dynamic" fixing ability. Pilots had to estimate their position using only visual information. Each pilot indicated his own estimate on a chart by locating a model ship in the indicated channel. Similar data collection techniques were used at sea to obtain a measure of the pilot's estimated position. At sea, all position estimates were obviously dynamic.

The accuracy with which a pilot can translate his mental position estimate to a marked position on a chart independent of the accuracy of the mental estimate is of some interest. Although we have performed no definitive analysis on this question, there is some indication of error magnitude contained in the data. Pilots were asked at the same positions in the CAORF experimental channel to estimate both their actual distance from the channel centerline in feet and to indicate their position on the chart. The standard deviation of the distances estimated was 15.7 feet while measurements of the graphical estimates produced a standard deviation of 29 feet. Although the difference in standard deviations in this case was 13.3 feet, it should be noted that there is a probable error also in converting from a mental position estimate to a numerical distance. These questions are anticipated to be subjects of study in later CAORF experimental work.

Samples of data collected at CAORF are shown in FIGURES 3-1 through 3-4. There are two important properties of these data:

- a. Changing the AN configuration (adding buoys or changing placement) resulted in a change in position estimation accuracy.
- b. Position accuracy depended on the actual position of the ship relative to the AN.

These data also point to a number of other interesting trends that focus on the fixing process exercised by the pilots as described below.

Standard deviation data listed in FIGURE 3-1 show that adding ANs will, for certain configurations, cause the "static" estimation error in cross and along track positions to be reduced. Actual ship position for each of the configurations is identical. Standard deviation data in FIGURE 3-2 show the same trend with the additional experimental variable of estimating ownship's position at two locations. Static cross and along track standard deviations in position estimation change as a function of both the ship's actual position and AN configuration. Close inspection of cross track standard deviations, in the lower channels, shows a trend that may not have been expected. The cross track errors for positions farther away from the mid-channel gate buoys appear to be smaller than

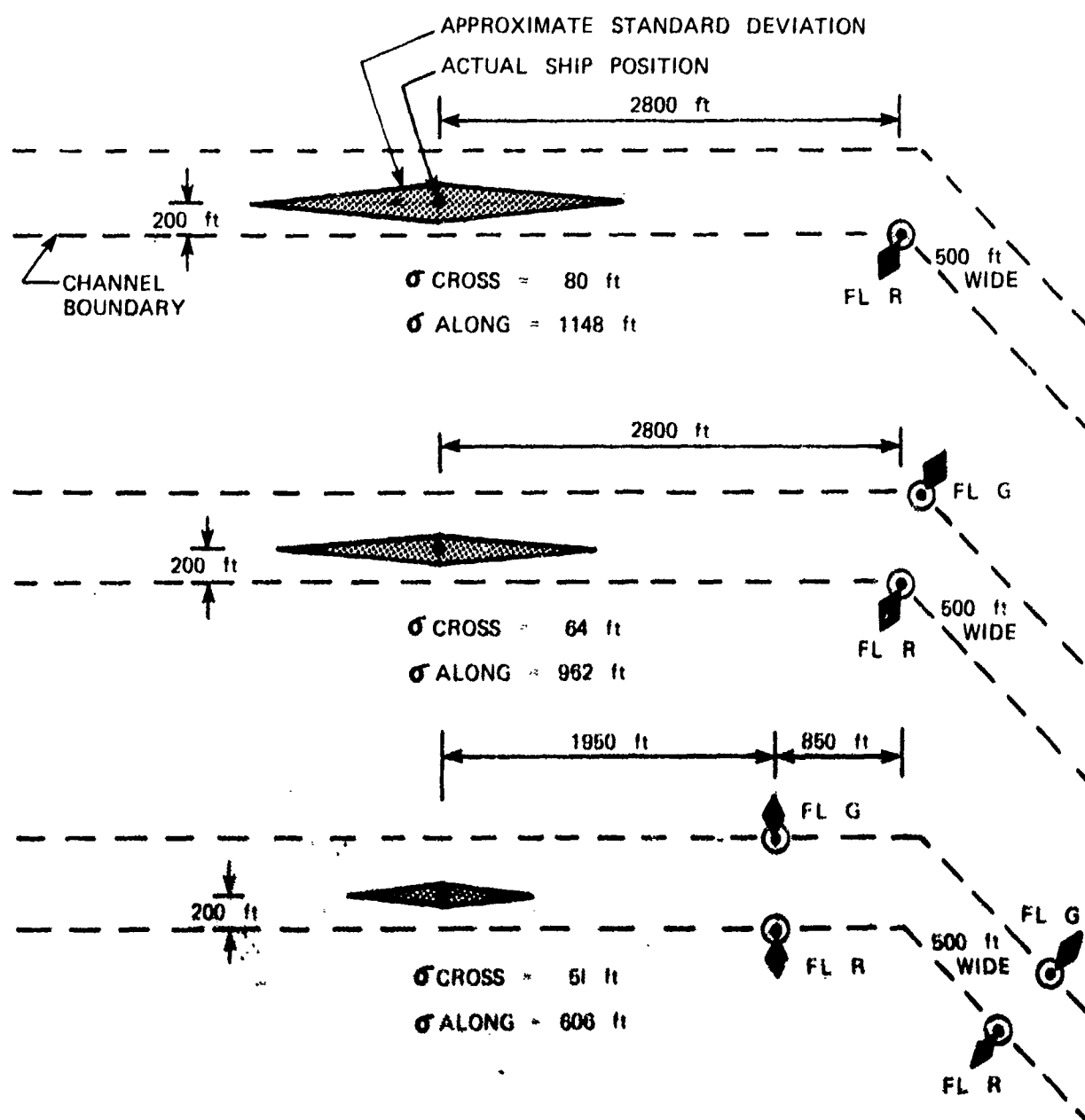


FIGURE 3-1. CROSS AND ALONG TRACK STANDARD DEVIATIONS IN PILOT'S STATIC ESTIMATED POSITION APPROACHING DIFFERENT AN CONFIGURATIONS (DATA COLLECTED AT CAORF)



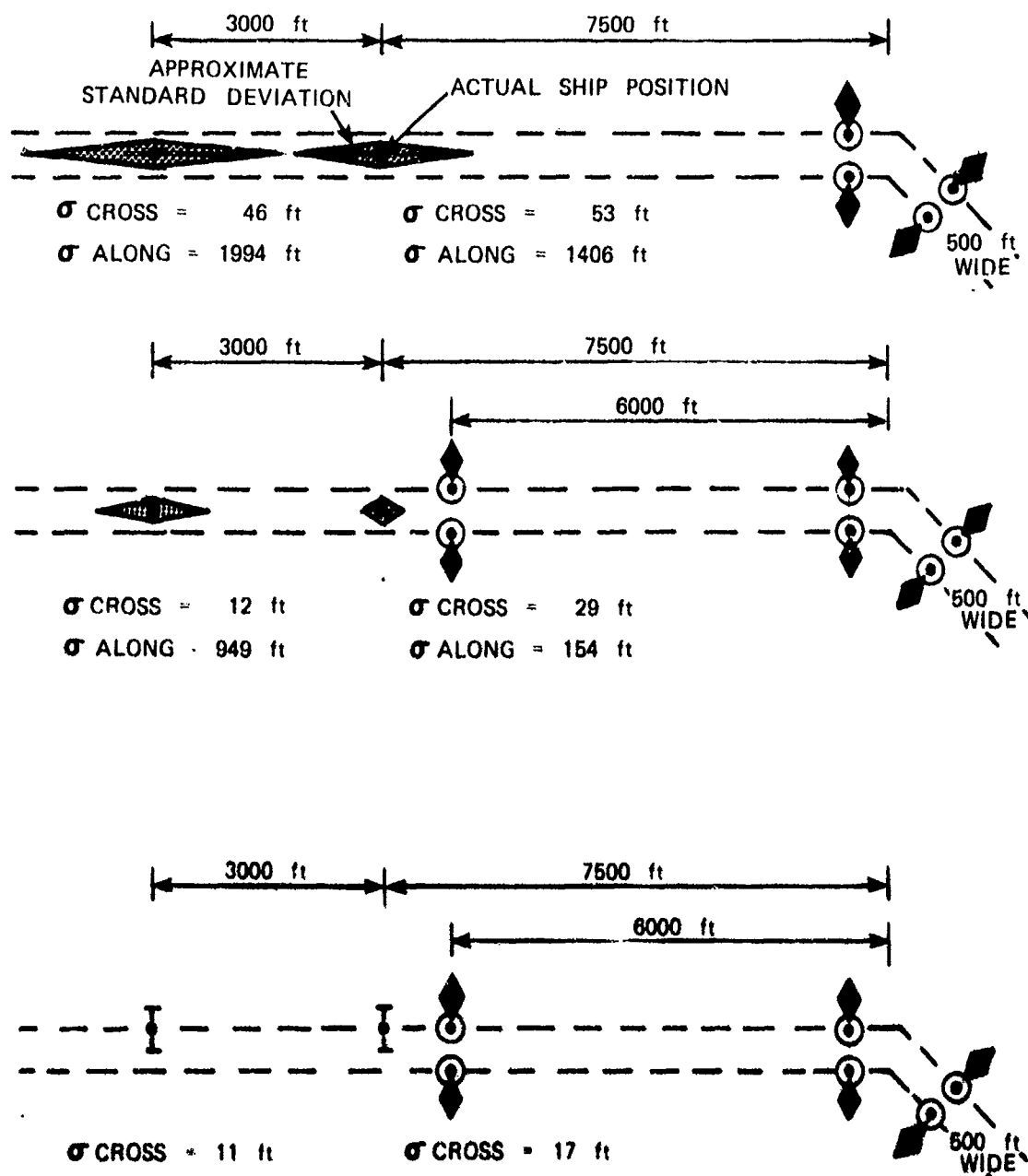


FIGURE 3-2. CROSS AND ALONG TRACK STANDARD DEVIATIONS IN PILOT'S STATIC ESTIMATED POSITION AS A FUNCTION OF ADDITIONAL BUOYS ALONG CHANNEL (DATA COLLECTED AT CAORF)

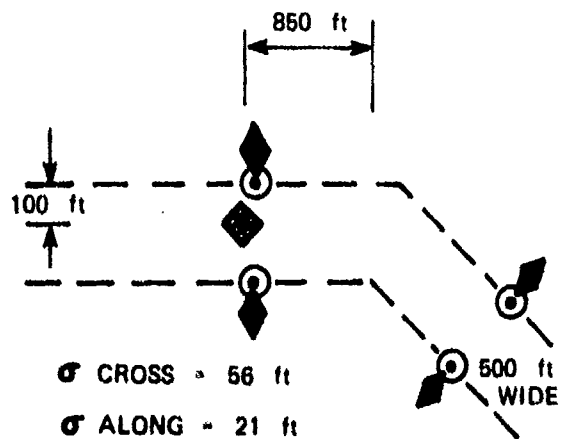
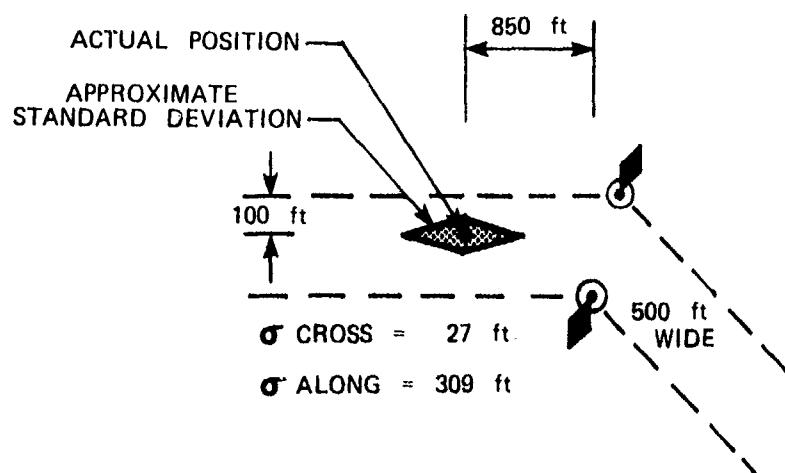


FIGURE 3-3. CROSS AND ALONG TRACK STANDARD DEVIATIONS IN PILOT'S STATIC ESTIMATED POSITION VERSUS DISTANCE TO GATED BUOYS (DATA COLLECTED AT CAORF)

those closer (e.g.,  $\sigma$  cross = 12 feet versus  $\sigma$  cross = 29 feet in the center of the channel, and  $\sigma$  cross = 11 feet versus  $\sigma$  cross = 17 feet at the edge of the channel).

This relationship may be explained when the buoy configurations are viewed as ranges. The farther away a ship is from the buoy gates, the smaller the vertical visual angle is between buoys. Coast Guard experience with ranges (reference 18) shows that the smaller the vertical angle, the more sensitive pilots are to changes in the horizontal angle. This important relationship between vertical and horizontal angles for ranges and all other ANs viewed relative to one another was identified early in our study and programmed into the AN routines. FIGURE 3-3 shows the limiting value of approaching gated buoys. The cross track standard deviation of position grows to 56 feet as the ship's bridge is placed between the buoys. Note that, in FIGURE 3-3, the along track error is reduced in size when the ship is abeam or between ANs. Accurate knowledge of along track positions seems to occur only when ANs are abeam.

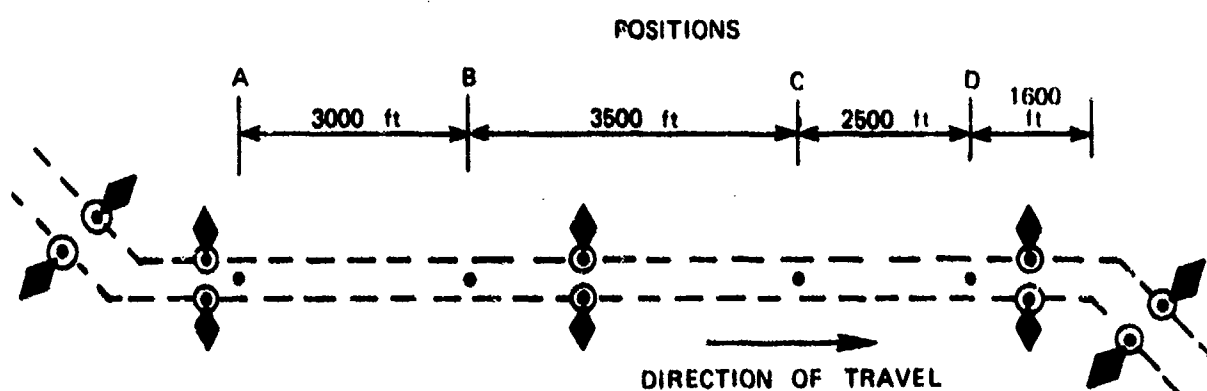
Differences between static and dynamic fixing ability are shown in FIGURE 3-4. Traveling left to right along a wandering path, pilots initially were less able to estimate the ship's cross track position when exiting the previous turn and just having passed through a pair of gated buoys. The initial standard deviation of the dynamic error at Position A is 63 feet versus the standard deviation of the static error of 11 feet. At Positions B, C, and D the standard deviations are nearly equal for the static and dynamic conditions. The difference noted between static and dynamic positioning accuracy has implications for our second set of measures of effectiveness which indicate how well a pilot maneuvers a ship along a channel, given only dynamic fix information.

The standard deviations of error in estimated position shown in FIGURES 3-1 through 3-4 are only indirect measures of safety. However, these particular measures provide considerable insight in the placement of ANs and in the processes by which pilots obtain an estimate of their position. Continued collection of data on such ship simulators as CAORF will provide additional valuable data and measures of the effectiveness of ANs.

The accuracy of position estimation measurement on ship simulators cannot alone provide a valid supporting data base for AN evaluation. Similar data must be collected at sea to provide the proper context in which to interpret simulator results. Previously we evaluated open sea fix accuracy via use of a satellite navigator as a standard (reference 6). Such methods would not suit coastal and pilot waters where accuracies in feet are sometimes required for ship control. What is required is a method of knowing ship position exactly as well as a method of quantifying the pilot's estimated position. To prove the feasibility of measuring a pilot's fix accuracy at sea and the value of fix accuracy as a measure of effectiveness indicative of relative safety, we performed an at-sea data collection aboard a 30,000-dwt commercial tanker.

A wide variety of AN systems was observed between Providence, Rhode Island, and Philadelphia, Pennsylvania. During preselected channel legs, efforts were made to obtain the pilot's estimated position and to locate the ship's exact position using visual surveying techniques. The pilot indicated ship position either as a numeric indication or by locating a scale model of the ship in the estimated position on an enlarged chart. Analysis of these data indicates that, although the pilot's fix accuracy varied greatly in alternate AN configurations, the relative safety of the ship remained constant as a function of available maneuvering room.

FIGURE 3-5 shows the absolute value of errors in cross-track position estimation. Each datum point represents one position in the channel where the pilot was asked to indicate his estimated position. At the same time data collectors obtained actual ship position by visually triangulating on a series of targets.



	A	B	C	D
	$\sigma$ CROSS	$\sigma$ CROSS	$\sigma$ CROSS	$\sigma$ CROSS
STATIC:	11 ft	29 ft	58 ft	58 ft
DYNAMIC:	63 ft	29 ft	61 ft	50 ft

**FIGURE 3-4. CROSS AND ALONG TRACK STANDARD DEVIATIONS IN PILOT'S STATIC AND DYNAMIC ESTIMATED POSITION (DATA COLLECTED AT CAORF)**

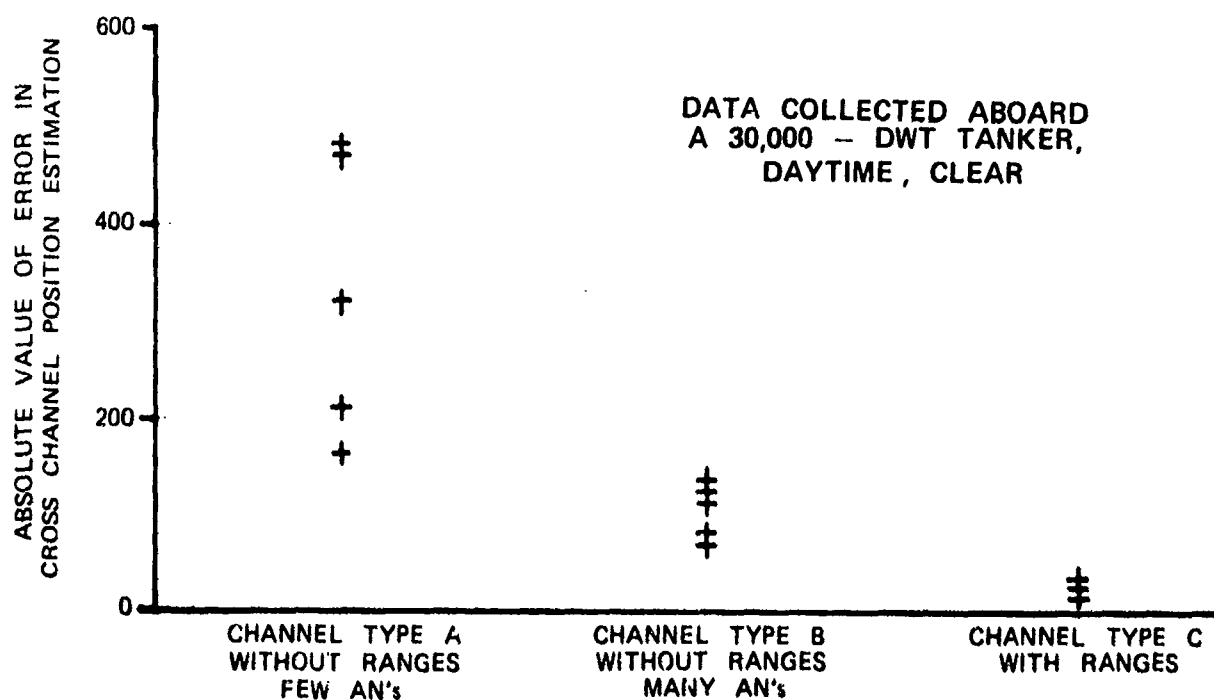


FIGURE 3-5. FIX ACCURACY VERSUS AN CONFIGURATION (ECLECTECH AT-SEA DATA BASE)

The three channel configurations relate to actual channels as follows:

Channel Type A, Without Ranges, Few ANs

- Fixed lighthouses every 4 nautical miles
- Floating ANs every 2-1/2 nautical miles
- Example - Brandywine and Miah Mauli Ranges, Delaware Bay

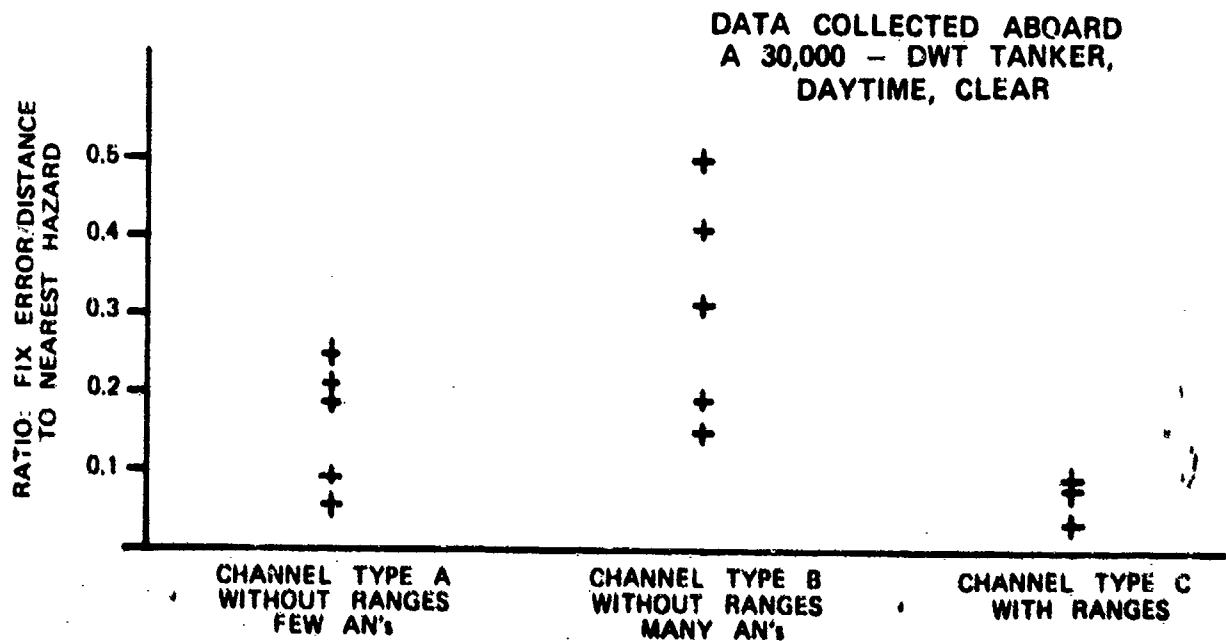
Channel Type B, Without Ranges, Numerous ANs

- Fixed beacons every 3<sup>+</sup> nautical miles
- Floating ANs every 1/2 to 3/4 nautical mile
- Example - Bullock Point, Conimicut Point, and Rumstick Neck Reaches, Narragansett Bay

### Channel Type C, With Ranges

- Range lights and day marks
- Floating AN every nautical mile
- Example – Reedy Island, Cherry Island, and Bellevue Ranges, Delaware River

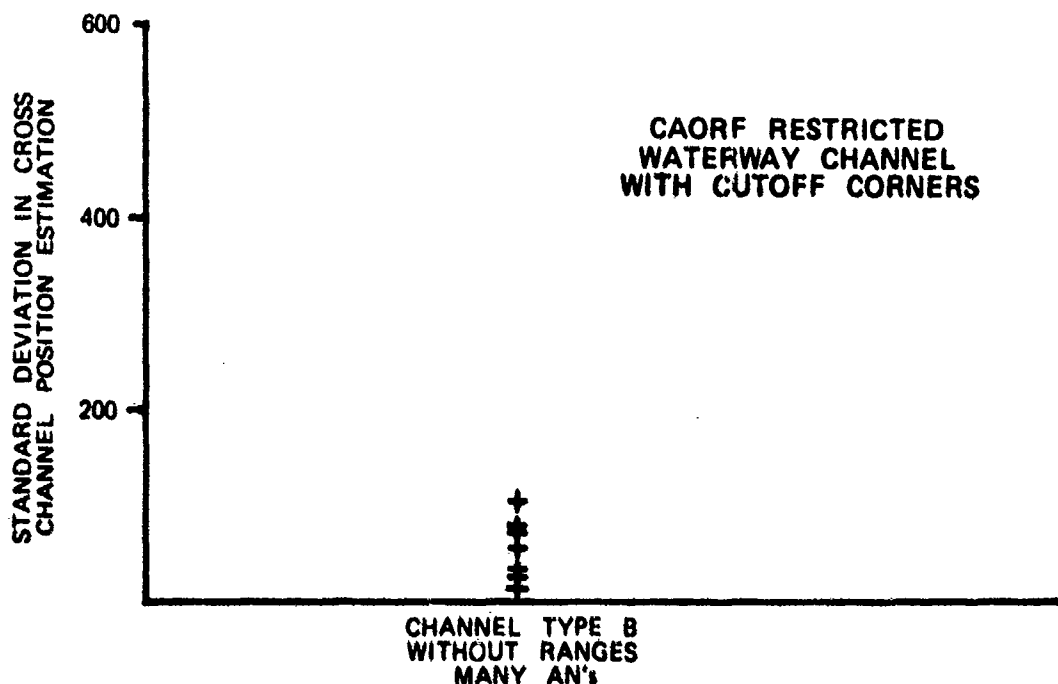
The range in fix accuracy between the various AN configurations is not surprising given the large distance between reliable (fixed) ANs in the three configurations. Note that these fix accuracies seem to provide an acceptable level of safety in these channels as a function of maneuvering room available. Data in FIGURE 3-6 indicate values of the error in fix estimation (feet) divided by the distance from the actual ship position to the nearest grounding hazard (feet). These data indicate that the fix accuracy observed was always equal to or less than one-quarter to one-half the distance to the nearest hazard. These data provide an indirect measure of the safety provided by the ANs in the channels observed. The extent to which a ratio of one-half represents a threshold value for AN design is unknown. Further compilation of such data across other AN configurations aboard different ships and under different weather conditions will aid in defining empirically supportable standards for AN design.



**FIGURE 3-6. FIX ACCURACY/HAZARD DISTANCE RATIO VERSUS AN CONFIGURATIONS (ECLECTECH AT-SEA DATA BASE)**

Data in FIGURES 3-5 and 3-6 were compared to the dynamic fix data compiled for the restricted waterways experiment at CAORF. FIGURES 3-7 and 3-8 show fix accuracy and hazard distance ratio data gathered at CAORF under similar conditions to those encountered at sea. Fix accuracy and hazard distance ratios indicate the pilot's ability to estimate where the particular spot on which he is standing is located relative to the channel or nearby hazards given the available AN configuration. This ability is a function of the position formation available to the pilot and the skill with which he uses it but is essentially independent of the size of platform on which he is located. The difference in size between the 80,000-dwt ship at CAORF and the 30,000-dwt tanker would not affect the comparison of these performance measures. The similarity of at-sea data to CAORF data is remarkable given that the data are compiled across 10 pilots and in several different channels.

*The close fit of the CAORF data to the at-sea, channel Type B<sup>4</sup> data confirms the validity of using CAORF in gathering portions of the data required for the development and validation of AN performance models.*



**FIGURE 3-7. FIX ACCURACY VERSUS AN CONFIGURATION (CAORF RESTRICTED WATERWAYS DATA)**

<sup>4</sup> The CAORF restricted waterways channel falls into the Type B category by virtue of its 3/4-nautical mile buoy spacing and lack of ranges.

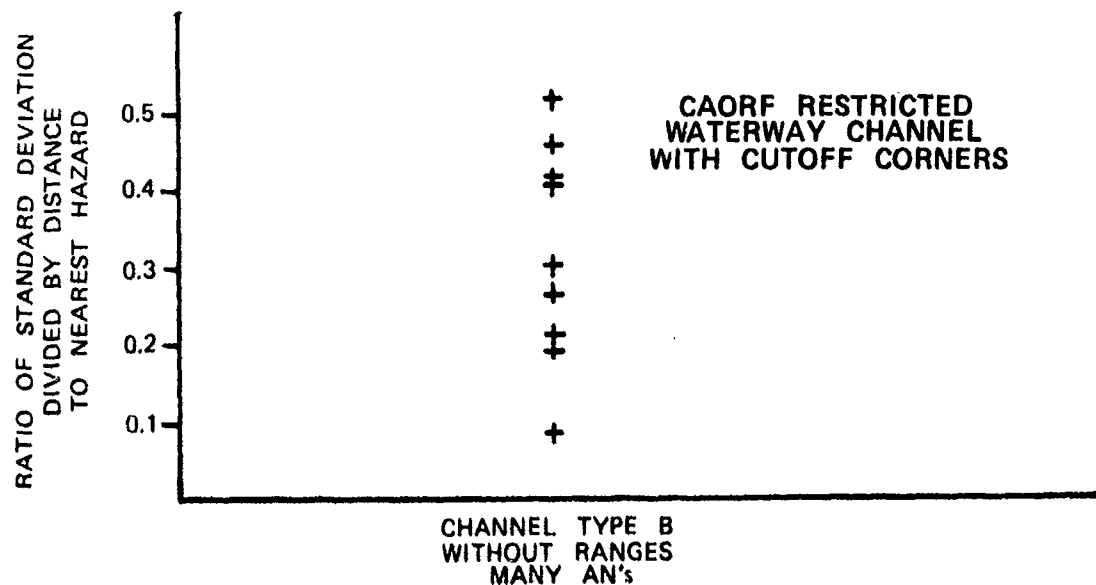


FIGURE 3-8. FIX ACCURACY/HAZARD DISTANCE RATIO VERSUS AN CONFIGURATION (CAORF RESTRICTED WATERWAYS DATA)

Comparing fix accuracy data collected at sea to CAORF data supports the partnership relationship between these two data sources. Fix data gathered at sea were necessarily limited to the use of one pilot on each voyage in a wide variety of channels. At CAORF, groups of many pilots can be evaluated at the same time in identical channels yielding a more prolific source of data for extrapolation in the AN model.

The multiple sources of fix data have yielded a number of different data formats for representing the fix accuracy measure of effectiveness (e.g., standard deviation of error, absolute error of fix, hazard distance ratio). The variety of data formats provides flexibility to meet the requirements of different end users. Our approach in gathering and analyzing fix and piloting accuracy data was to use the best and most easily understood formats suitable to the data on hand. As future data are collected, additional formats will be devised to indicate performance of ANs relative to the measure of effectiveness of fix and piloting accuracy.



### 3.2 NAVIGATING AND STEERING ACCURACY

Navigating and steering accuracy is a measure of a master's, mate's or pilot's ability to steer particular vessels, in specified geographic areas, given a specific set of ANs. Navigating and steering accuracy for a single passage along a channel may be represented as the variation in track line along the channel. This measure may be transformed into a distribution of swept width, summed along the entire channel. Analysis of many ships' passages in a particular channel can be represented by distributions of swept width. The probability that swept width would ever cross a grounding hazard provides a good indication of the probability of grounding. The variability of the tails of the swept width distribution (i.e., those portions of the distributions which describe the probability that a portion of the ship will extend to port or starboard of the desired track's width) indicates the relative controllability of the ship in a particular channel. As such, these data may represent one measure of the relative safety of navigating the channel.

Many data bases are available to demonstrate that navigating and steering accuracy data are measurable both at sea and on ship simulators and that these data are sensitive to changes in AN configurations. At-sea data are available from both a British research study and the at-sea data bases compiled at Eclectech Associates. Data from the CAORF restricted waterways experiment have also recently been made available. Examples of these data are discussed below.

At-sea data collected by the National Physical Laboratory in England (reference 19) demonstrated the feasibility of documenting ship's tracks in piloting waters and of studying various piloting and steering phenomena in such waters. Data in FIGURE 3-9 illustrate typical computer-generated track reconstructions from this study. Positions were determined by land-based visual surveying instruments; heading was recorded aboard the vessel. The advantage of entering this data in a computer provided the opportunity to analyze the data in several ways.

Data in FIGURE 3-10 illustrate measures of swept width recorded along the straight portion of the channel. The maximum swept width of 70 meters permits a first order evaluation of the safety of these ships in transiting the 210-meter wide channel. Relative to safety, not only the maximum swept width is of interest but also the variability of the path. The maximum swept width was most probably (but not necessarily) caused by the pilot purposefully changing the position of RHINE MARU (outbound) from the port half of the channel to the starboard half or, alternately, on BREMEN EXPRESS (outbound) allowing the ship to set slightly to port, then correcting the set halfway along the channel. Also important in terms of safety are the oscillations in track and swept width of RHINE MARU (inbound) as she turned into the channel leg (moving right to left in the diagram). These data indicate the effectiveness of the available ANs in giving the pilot sufficient information to straighten the ship onto the track. The oscillations are indicative of the pilot's total ability to determine his position and steer the ship via orders to the helmsman, who may also have contributed to the track variability while complying with the orders. (It is unknown if course or rudder commands were given in this situation.) The extremes of the oscillations in this example are shown to be 20 meters, 10 percent of the channel's width of 210 meters.

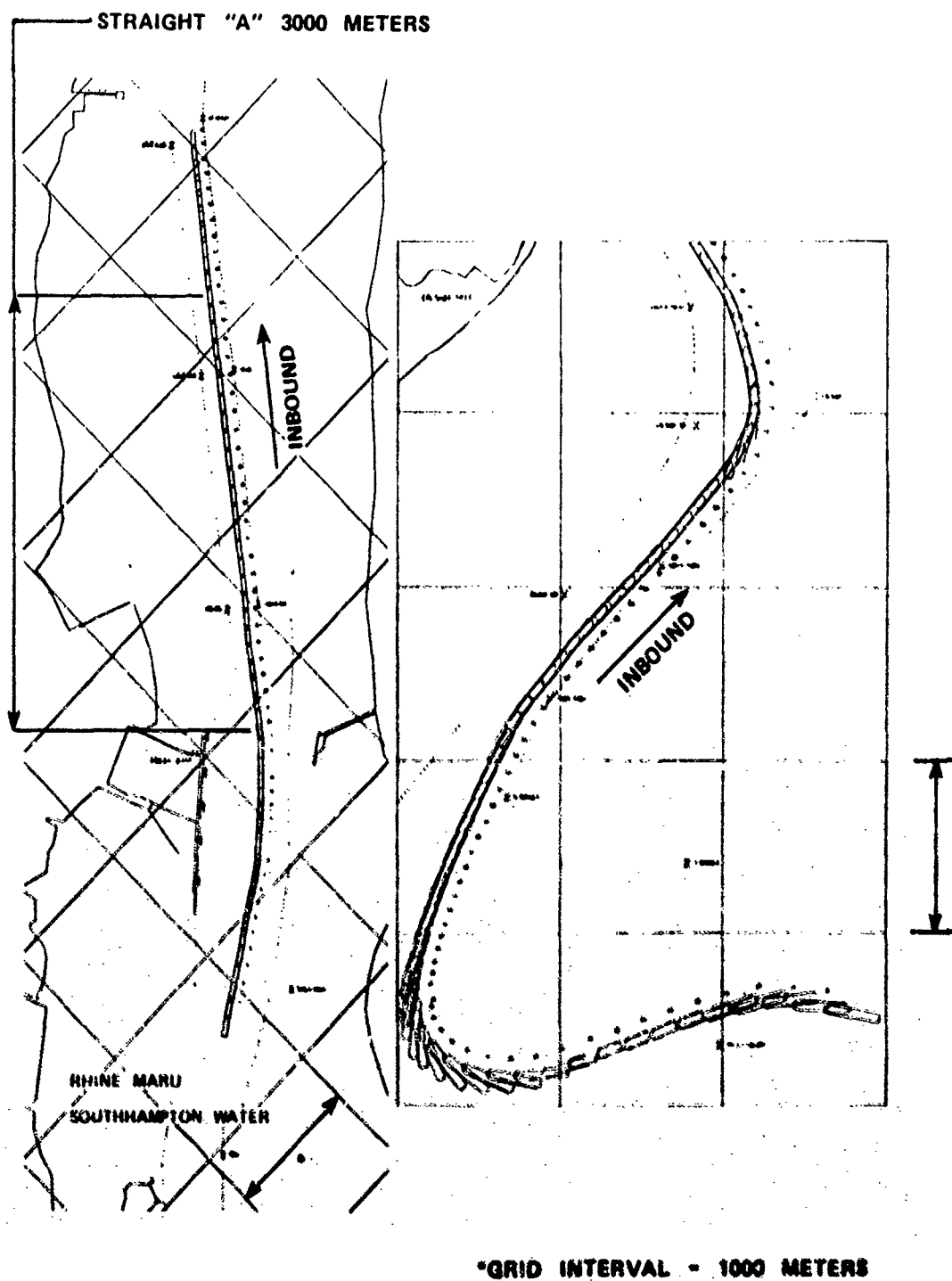


FIGURE 3-9. SHIP TRACK RECORDED, STRAIGHT CHANNEL

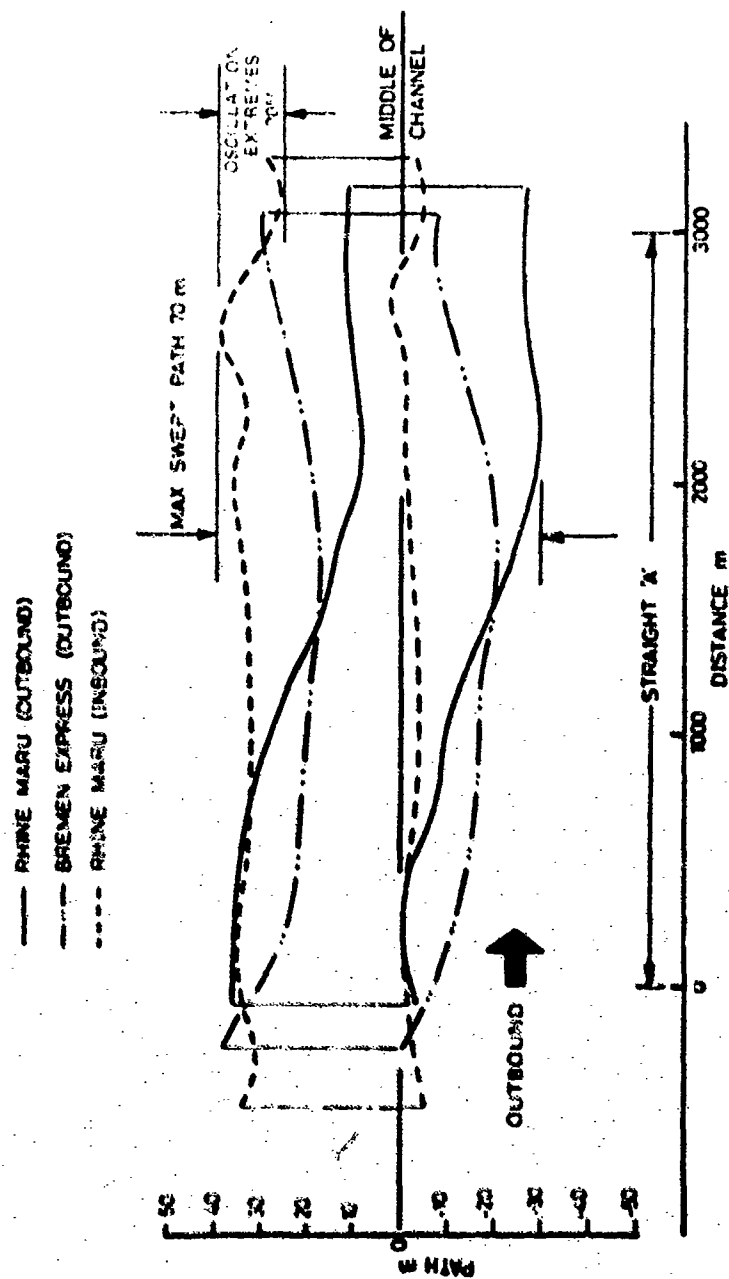


FIGURE 3-10. SWEEP PATH WIDTHS IN SOUTHAMPTON WATER

Swept width data recorded by the British were also analyzed by grouping inbound and outbound tracks in the outer channel. FIGURE 3-11 illustrates general differences in tracks between inbound and outbound VLCCs. The difference in width between inbound and outbound tracks is probably caused by pilot strategies rather than variations in position estimations by pilots. FIGURE 3-12 illustrates a breakdown of the inbound data by the pilot in command. These data show that a single pilot (A) was able to maneuver four different ships under four different current conditions, along a path he seems to have selected as optimum. These data illustrate that this area probably has sufficient ANs since the differences in pilot A's tracks are only 60 meters relative to a channel width of 500 meters.

Ship maneuvering data related directly to available ANs was collected during our at-sea data collection trip in Narragansett Bay and the Delaware River. Data in FIGURE 3-13 show the cumulative swept width data versus various AN configurations. Channel Types A, B, and C are identical to those described in Section 3.1. These curves represent the percent of time that a particular section along the channel will be covered by any portion of the hull. For example, the middle section of Channel Type B will be occupied 0.5 or 50 percent of the time the ship is transiting the channel. The rest of the time the entire hull is either to port or starboard of this line. A section 150 feet in from the port side of the channel will be occupied only 25 percent of the time. If any of these curves extend over a grounding hazard, a potential for grounding would be indicated.

The variation in maximum swept widths and the steepness of the curves at either side potentially indicate performance of the various AN configurations. The swept width curves for Channel Type A (lighthouses every 4 nautical miles and buoys every 2-1/2 nautical miles) illustrate the largest maximum swept width value. Additionally, the low flat portion of the curve to the left may indicate a certain amount of wandering left versus a check of the wandering indicated by the right-hand portion of the curve.

An increase in the number of floating aids in Channel B (buoys every 1/2 nautical mile) reduced the maximum swept width and steepened the sides of the curves. There is still evidence of wander right and left in these data.

Adding range lights in Channel C reduced the maximum swept width even further, allowing ownship to easily maintain a position slightly to starboard of the centerline. A rapid falloff of curve to the right and left is evident, illustrating only a small tendency to wander.

The stepped form of the curves in FIGURE 3-13 indicates the discrete nature of our position information gathered every 2 to 3 minutes. Future data collection in these areas should be automated (electronic survey systems such as auto tape) to provide position samples every 15 to 30 seconds. Computer analysis of such data would yield smoother curves in the port and starboard side regions. Computer generated curves of cumulative swept width are illustrated in Section 4 as output curves of the AN performance model.

Preliminary data, which support cross track position and swept width as valid measures of effectiveness, are also available from the CAORF restricted waterways experiment. The upper curve in FIGURE 3-14 illustrates the swept width function for an AN configuration similar to Channel Type B data collected at sea. The maximum swept width value of 255 feet compares favorably with the sea value of 275 feet. Note, however, that the CAORF channel is 100 feet narrower than that encountered at sea; yet the maximum swept widths remained nearly the same. One potential conclusion drawn from this relationship is that a 255- to 275-ft cross channel distance is required for

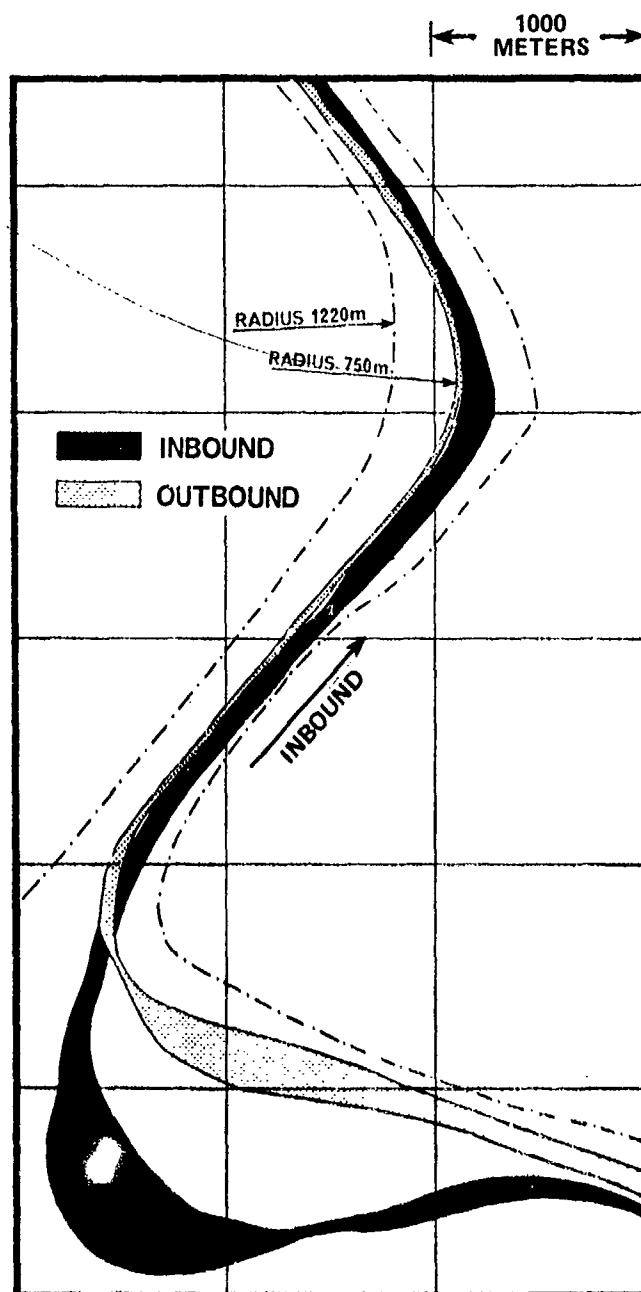


FIGURE 3-11. GENERAL DIFFERENCES OF TRACK BETWEEN INBOUND AND OUTBOUND VLCC'S.



DATA COLLECTED ABOARD  
A 30,000 - DWT TANKER,  
DAYTIME, CLEAR

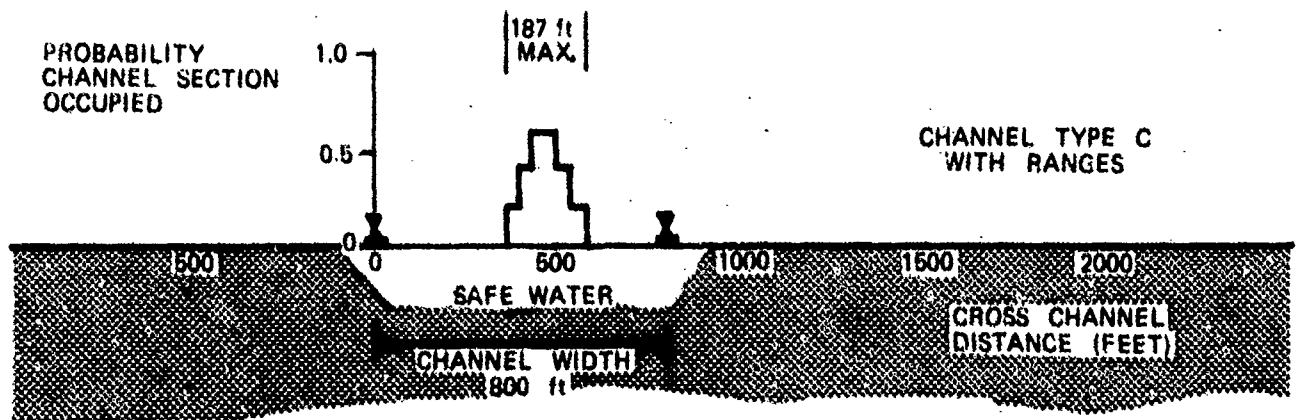
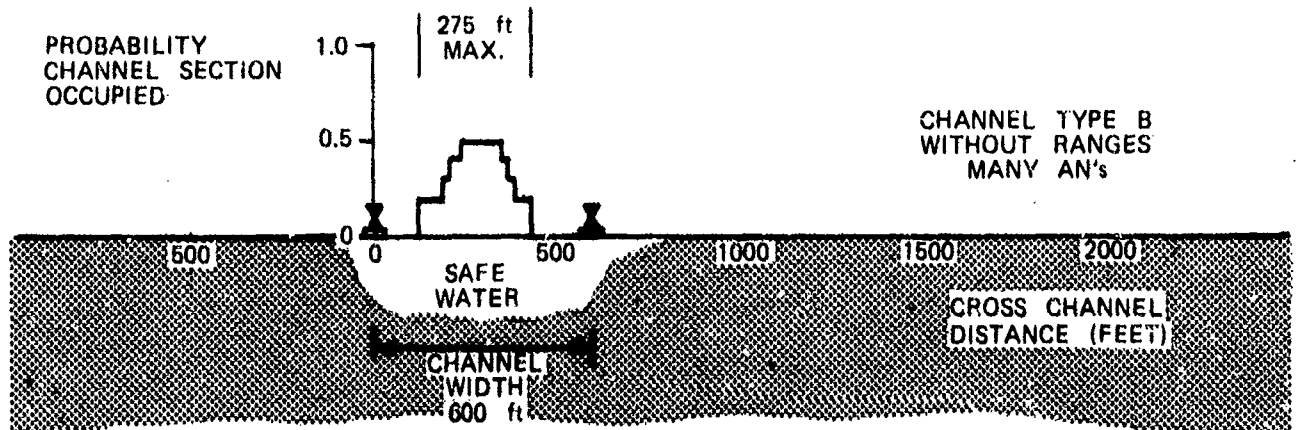
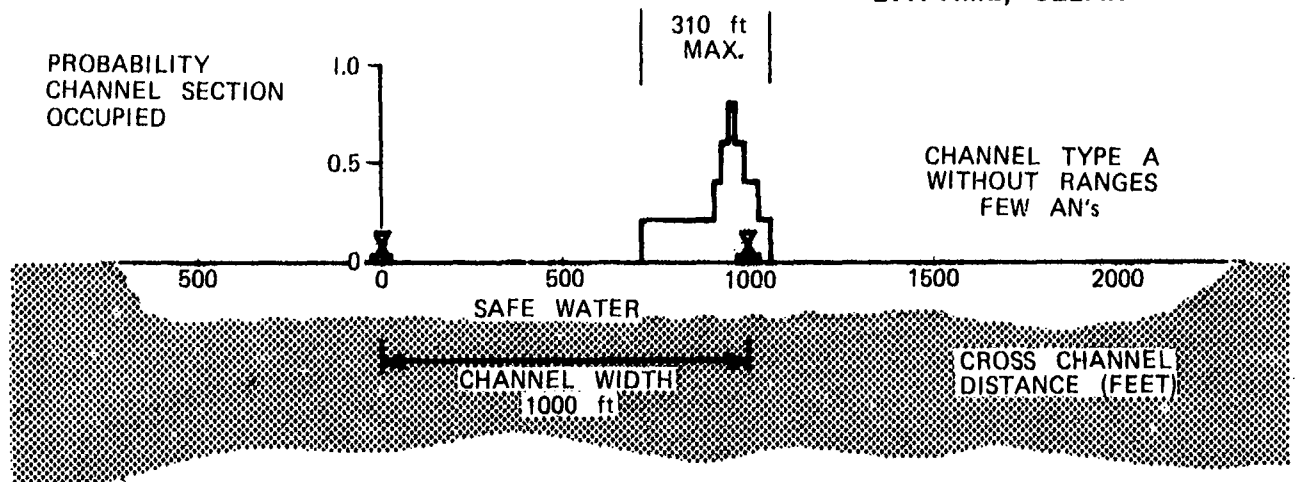


FIGURE 3-13. SWEEP WIDTH PROBABILITY FUNCTIONS VERSUS AN CONFIGURATIONS  
(ECLECTECH AT-SEA DATA BASES)

DATA RECONSTRUCTED FROM  
PRELIMINARY RESTRICTED  
WATERWAYS TRACK PLOTS

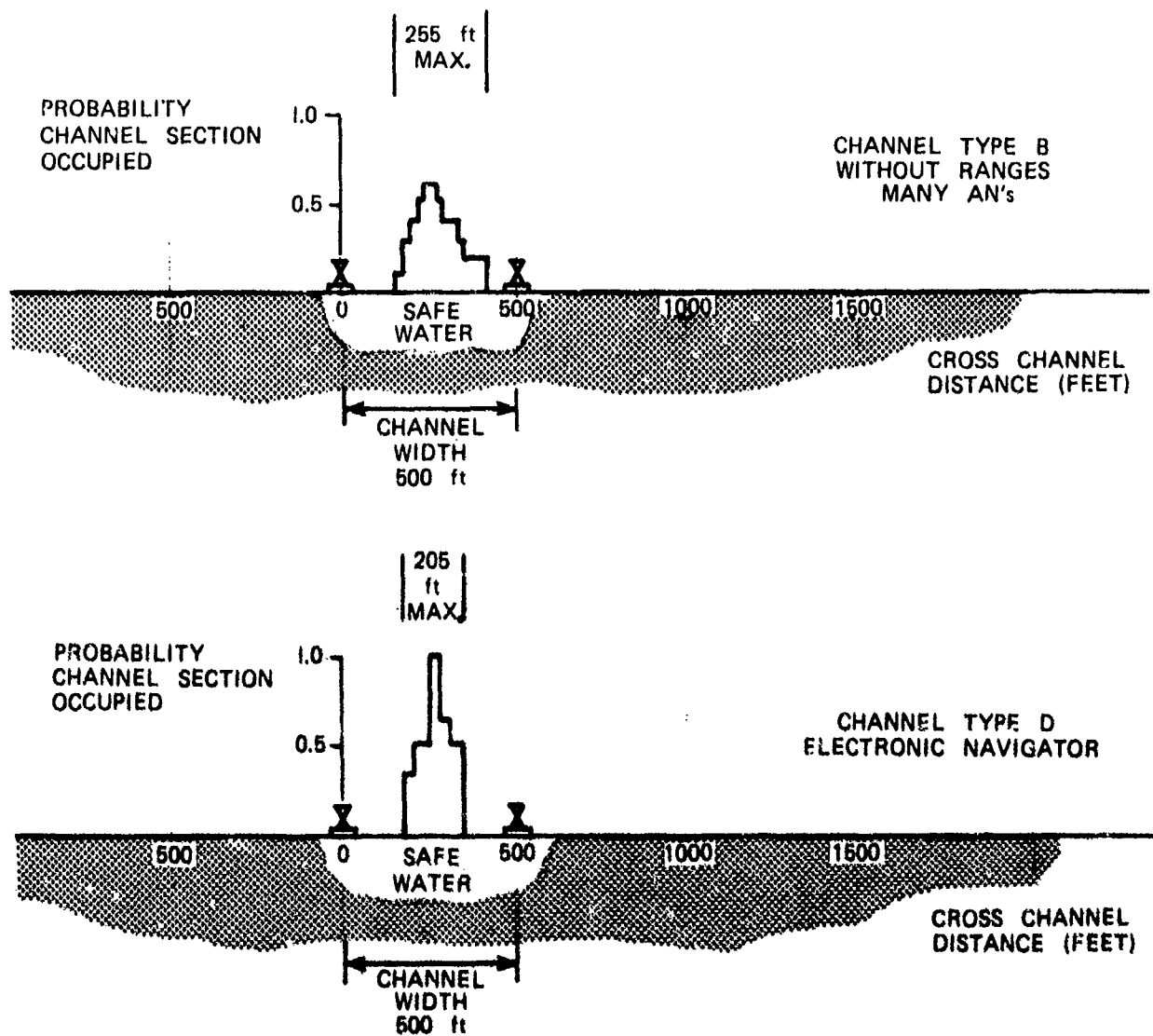


FIGURE 3-14. SWEEP WIDTH PROBABILITY FUNCTIONS VERSUS AN CONFIGURATIONS  
FOR CAORP RESTRICTED WATERWAYS



maneuvering given floating aids in confined channels. This distance is not necessarily the minimum, because at-sea data indicated only 187 feet were necessary in the channel marked with ranges. Supporting data, collected at CAORF, shown in the lower curve of FIGURE 3-14 (Channel Type D, electronic navigator) indicate that, given numeric values of cross channel position (feet left or right) and velocity (feet per minute left or right), the maximum swept width was held to 205 feet. This comparison of maximum swept widths has not been tested to determine whether there exist significant differences between the means of the distributions from which the samples were taken. The amount of change of maximum swept width between Channel Type B (255 to 275 feet) and Channel Types C and D (187 to 205 feet) would suggest that a significant difference may be found when sufficient data are available. In contrast the change between Channel Type C (187 feet) and Channel Type D (205 feet) suggests that no significant difference may be found.

The effectiveness of using swept width information for evaluation of electronic positioning information has similarly been demonstrated by an advanced display study currently being conducted on a ship's display simulator at Eclectech Associates. Data in FIGURE 3-15 illustrate the differences that result from using a normal radar display versus an advanced radar display which indicates the location of all ANs and also superimposes on the radar display a synthetic picture of channel boundary lines and centerlines. The channel negotiated by subject pilots was, in this case, the Kill Van Kull between The Narrows and Newark Bay. The bar graph in the upper corner of this figure indicates that the mean distance to the channel centerline calculated along the track was less for the advanced display. Swept width cumulative functions are currently being compiled for these data.

A final application of swept width as a measure of AN effectiveness is the evaluation of traffic passing situations. Preliminary data released for the restricted waterways experiment indicate that improving ANs will change the cumulative swept width functions calculated at the time of CPA (closest point of approach). Data curves in FIGURE 3-16 illustrate the effect of placing more ANs in Channel Type B versus Channel Type A. The mean swept width position is farther from the traffic ship; the minimum CPA is larger (145 feet versus 95 feet); and the maximum swept width is smaller (170 feet versus 190 feet). Conclusions which might be drawn from these data are that given adequate ANs (Channel Type B), the pilots could more reliably maneuver ownship closer to the right channel boundary in an effort to widen the distance between the two ships. This change in behavior impacts both ship safety and traffic facilitation. Swept width data will aid in selecting safe areas for passing and thus aid traffic flow in channel systems.

An overview of all the data pertaining to piloting and steering accuracy indicates that this measure of effectiveness is sensitive to both changes in short range ANs (buoys, lighthouses, ranges, etc) and changes in long range aids (such radio aids as LORAN-C, mini LORAN-C, Decca, etc). This measure also provided an indication of the complete interrelation of traffic safety and traffic facilitation.

*It is an important aspect of this measure that we and others have demonstrated the feasibility of measuring and quantifying piloting and steering accuracy both at sea and in ship simulators.*

The particular format of data presentation has been shown by examples to range from pictorial charts and band widths to cumulative density functions. The latter, probabilistic measures are most suitable for indication of relative safety afforded ownship and also traffic ships.

An added consideration across the CAORF, at-sea, and EA pilot data bases is the issue of ship size. The at-sea data were collected on a 30,000-dwt ship while both

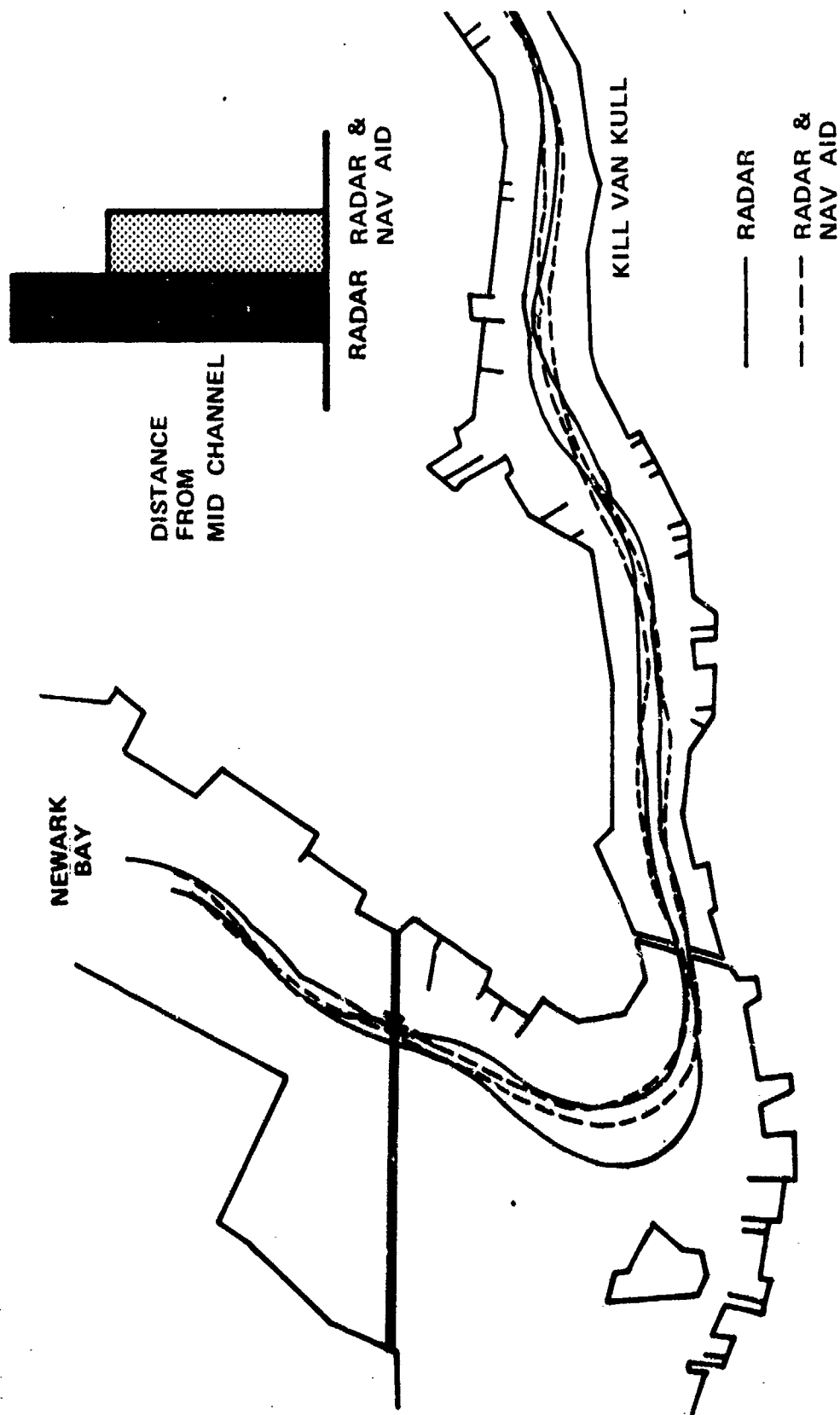


FIGURE 3-15. DIFFERENCES IN SWEEP WIDTH BETWEEN USE OF RADAR ALONE AND RADAR WITH NAVIGATION AID INFORMATION

DATA RECONSTRUCTED FROM  
PRELIMINARY RESTRICTED  
WATERWAYS TRACK PLOTS

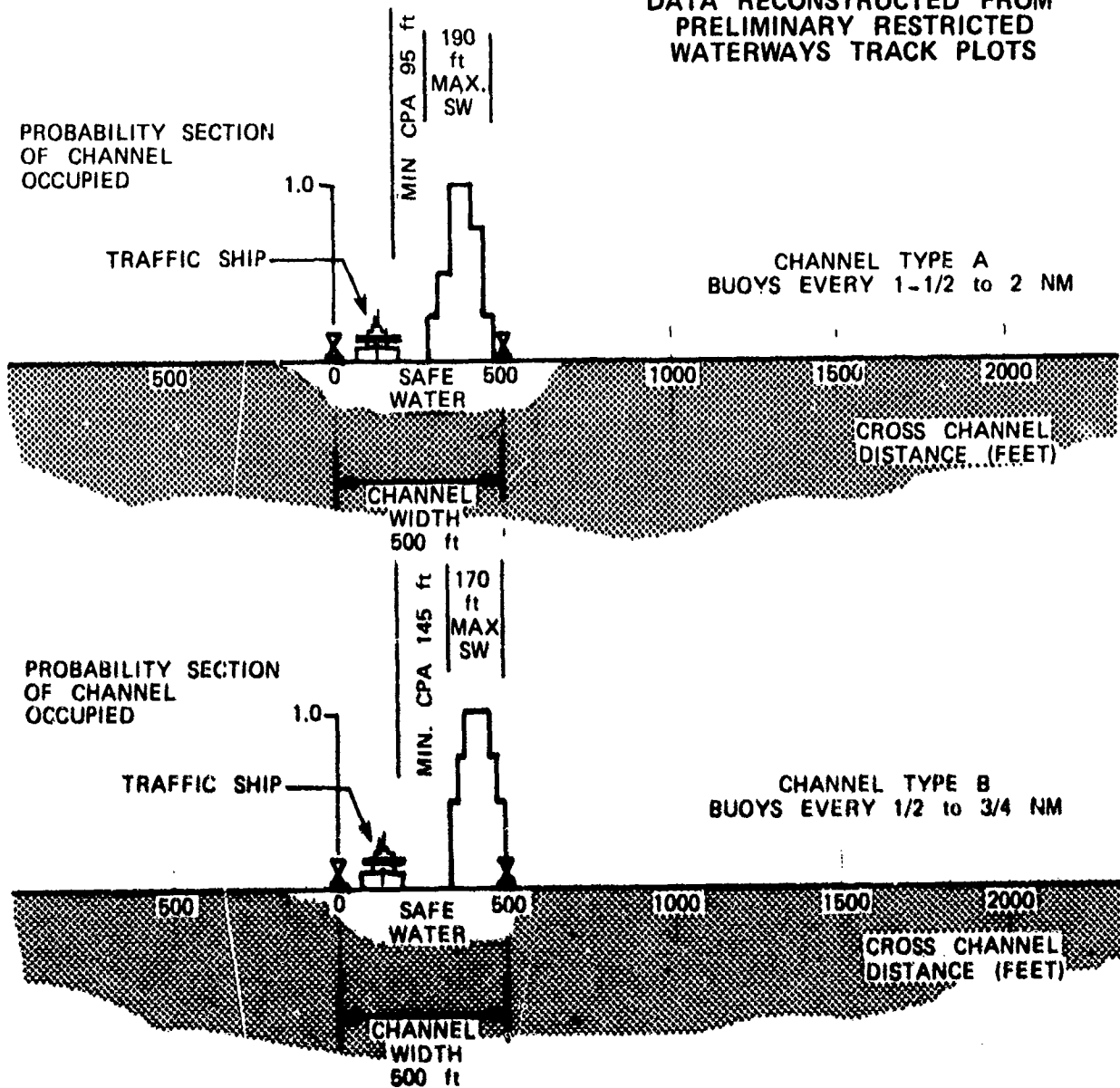


FIGURE 3-16. SWEEP WIDTH PROBABILITY FUNCTIONS VERSUS AN CONFIGURATIONS AT TIME OF CPA TO TRAFFIC VESSELS (CAORP RESTRICTED WATERWAYS)

simulator data bases were collected using an 80,000-dwt ship. The fact that similar trends resulted may indicate less importance of the variable of ship size in the final AN model. We estimate that the final results will apply to fairly large groupings of tonnage and ship characteristics. This variable is easily examined in Phase II; these preliminary results indicate that this testing at sea and on CAORF may not be as extensive as originally thought.

### 3.3 TRAFFIC CAPACITY

Traffic capacity is a measure of the ability of a particular channel or set of channels to handle a specified mix of vessels arriving at random or dependent time intervals. The principal indicator of traffic capacity is delay time per ship type in transiting a particular channel or a set of channels (e.g., sea buoy to berth). This measure can easily be related to costs for delay and thus serve as an economic tradeoff factor. Delays in transiting time in a harbor present potential economic losses to commercial vessels using the harbor waterways. Real costs associated with delays are proportional to the per hour cost of operating the vessel (reference 20). The daily operating costs incurred by particular vessels and their potential maneuvering (or transiting) speeds are listed in TABLE 3-1. A delay of one hour in transiting the harbor will cost a ship operator 1/24 of the costs listed in TABLE 3-1. Annual costs are calculated by multiplying this value times the number of trips made into the harbor each year and the probability that the delay will be incurred each trip. Total costs to the shipping industry (foreign and U.S.) are calculated by projecting savings across the annual port traffic volume.

TABLE 3-1. PER DIEM COSTS OF OPERATING COMMERCIAL VESSELS AND MANEUVERING SPEEDS

VESSEL TYPE	COST PER* DAY (\$)	MANEUVERING SPEED
80,000- to 150,000-dwt tankers	24,650	10 KNOTS
30,000- to 80,000-dwt tankers	20,380	10 KNOTS
12,000- to 30,000-dwt tankers	19,230	12 KNOTS
container ships	31,150	18 KNOTS
feeder container ship	18,560	16 KNOTS
general cargo C-6	24,420	12 KNOTS
bulk carriers	20,540	12 KNOTS
tug and tow	8,000	8 KNOTS
fishing trawlers	1,980	6 KNOTS

\*Figure for 1977 calculated from 1975 values. U.S. Maritime Administration, Office of Domestic Shipping, Division of Ship Management.

Faster ships might incur greater transiting delays because they may be required to slow in poorly marked areas or they may not be able to overtake and pass slower vessels in certain channels. Note in TABLE 3-1 that costs for operating faster ships are generally greater than for slower vessels. The inability of a particular turn or channel to allow two-way traffic may delay all vessels using that channel. Restricting all traffic flow for arrival and departure of a liquid natural gas (LNG) carrier will delay all vessels.

Data supporting traffic delay as a measure of AN effectiveness are lacking for major ports in the world today. Compilation of such data is just commencing at the Port of Rotterdam (reference 21) and the Port of New York (reference 22). The practicality of measuring and relating vessel delays, vessel type, and AN configurations in channels was demonstrated by a vessel traffic survey of New York Harbor. FIGURE 3-17 is a composite picture of vessel locations plotted from radar every 1/2-hour, for a 24-hour period, for the lower bay of New York Harbor. Vessel positions relative to channel boundaries are indicated by designation of lighted buoy locations.

The analysis of radar image photographs taken every minute at New York Harbor yielded a 24-hour distribution in traffic type. Vessel types (ship, tug and tow, and dredge) were identified by classifying radar return images; unfortunately, ship identity, carrier type, and maneuvering speed were not collected with this data. The data in FIGURE 3-18 indicate that ship traffic peaked in the morning (0600 hours) and in the afternoon (1400 to 1600 hours) and that ships made up most of the vessels moving in the channels.

A sample distribution of vessel speeds in lower New York Harbor was generated by measuring distances traveled between radar pictures and calculating speeds for the vessels present. Data in FIGURE 3-19 represents a frequency density function of speeds in New York's lower bay. A further subdivision of this speed data by channel would be required to identify potential slowing due to alternate AN configurations or insufficient ANs for safe passing.

Future collection in selected channels could best be gathered through timed photography of both radar information and a display of collision avoidance true motion vectors. Commercially available collision avoidance radar displays (Iotron and IBM) automatically track up to 40 vessels, designating each vessel with a vector whose length is proportional to the vessel's speed and whose direction is true course of the vessel. Analysis of sequential photographs of collision avoidance displays would immediately show changes in speed for particular channels and traffic congestion. VHF communications or port data would be used to determine vessel identity, size, and speed capability.

Traffic delay as a measure of effectiveness of ANs in the United States will apply mainly to such congested ports as the Houston Ship Channel or the Port of Baltimore. Many major ports such as the Port of New York are so widespread geographically that congestion seldom occurs. Application of the measure in seemingly uncongested ports can be limited to specific key channels that occasionally back up (e.g., Kill Van Kull in New York).

The ultimate use of traffic delay time as a measure of economic cost to commercial traffic can be pursued at the discretion of Coast Guard Headquarters. Reductions in delays to shipping will return savings immediately to the ship operators using the port. The dollar return to regional economies will be through a long term decrease in freight rate and potential increased attraction of new shipping to the port area as a function of increased efficiency (i.e., reduced delays).

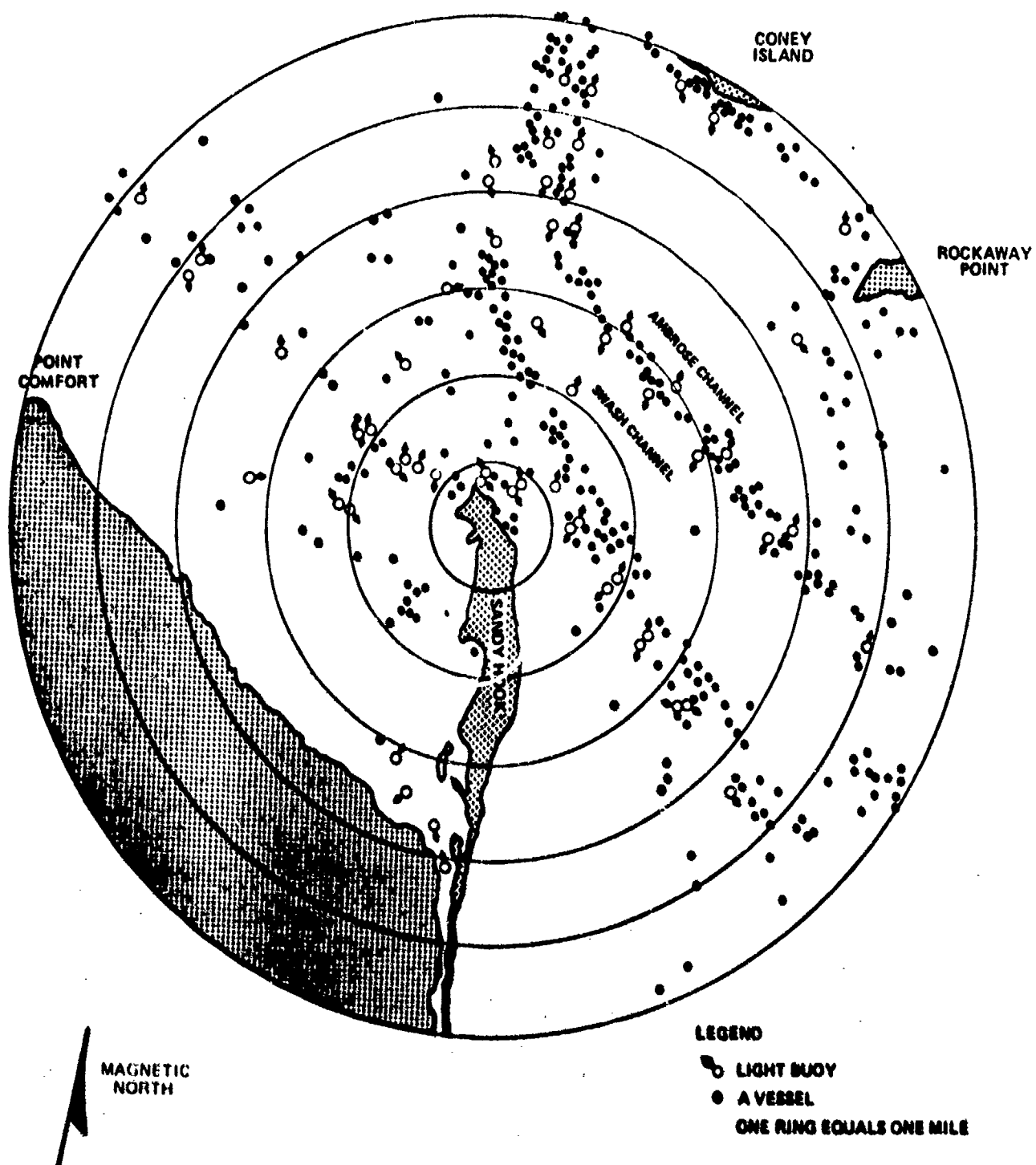
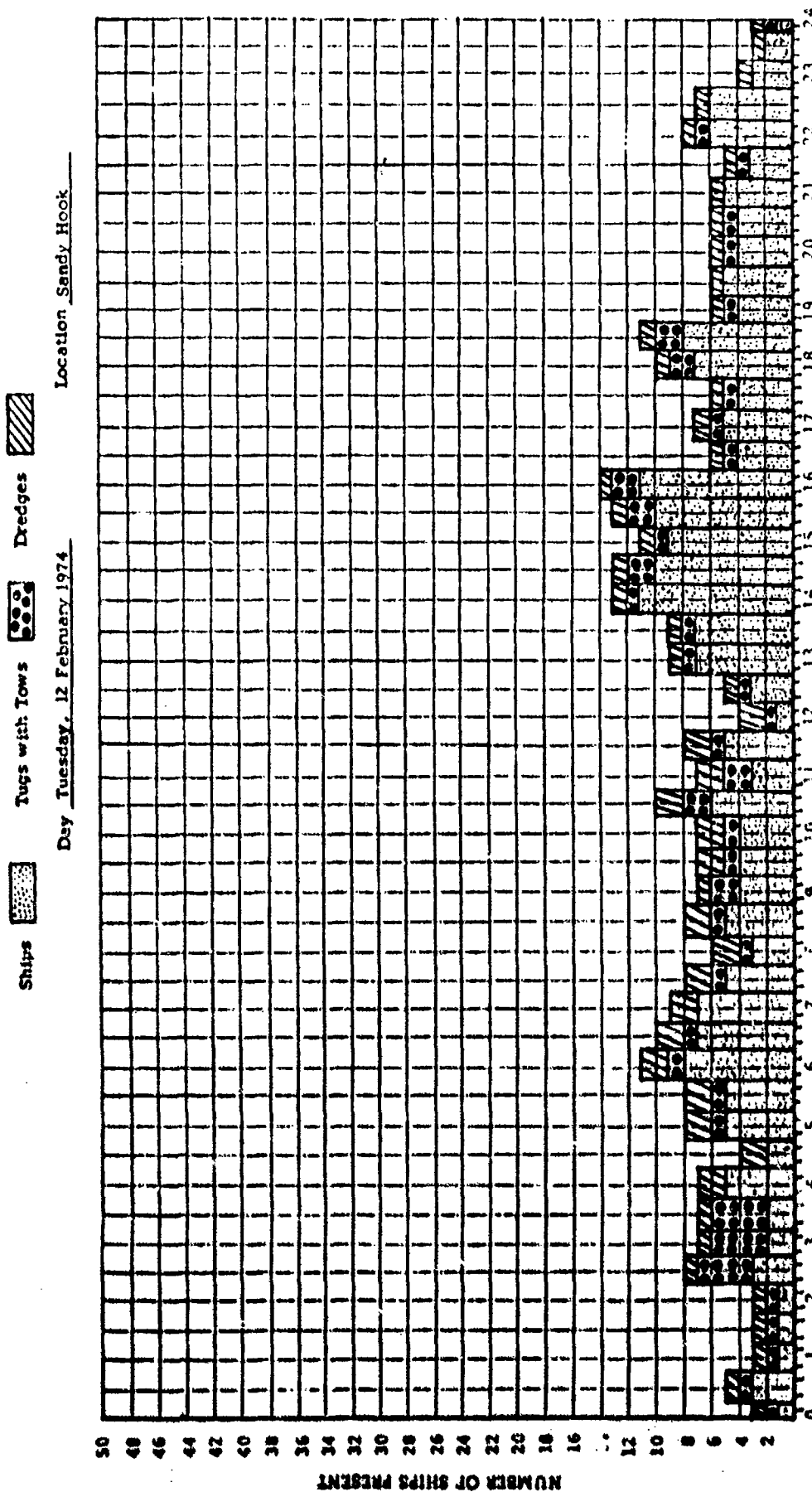


FIGURE 3-17. ROUTE IDENTIFICATION FOR SANDY HOOK (24 HOURS OF COVERAGE PLOTTED EVERY HALF HOUR, TUESDAY, 12 FEBRUARY 1974)



TIME OF DAY (HOURS)  
RADAR VESSEL DENSITY DATA

FIGURE 3-18. TIME OF DAY (HOURS) RADAR VESSEL DENSITY DATA

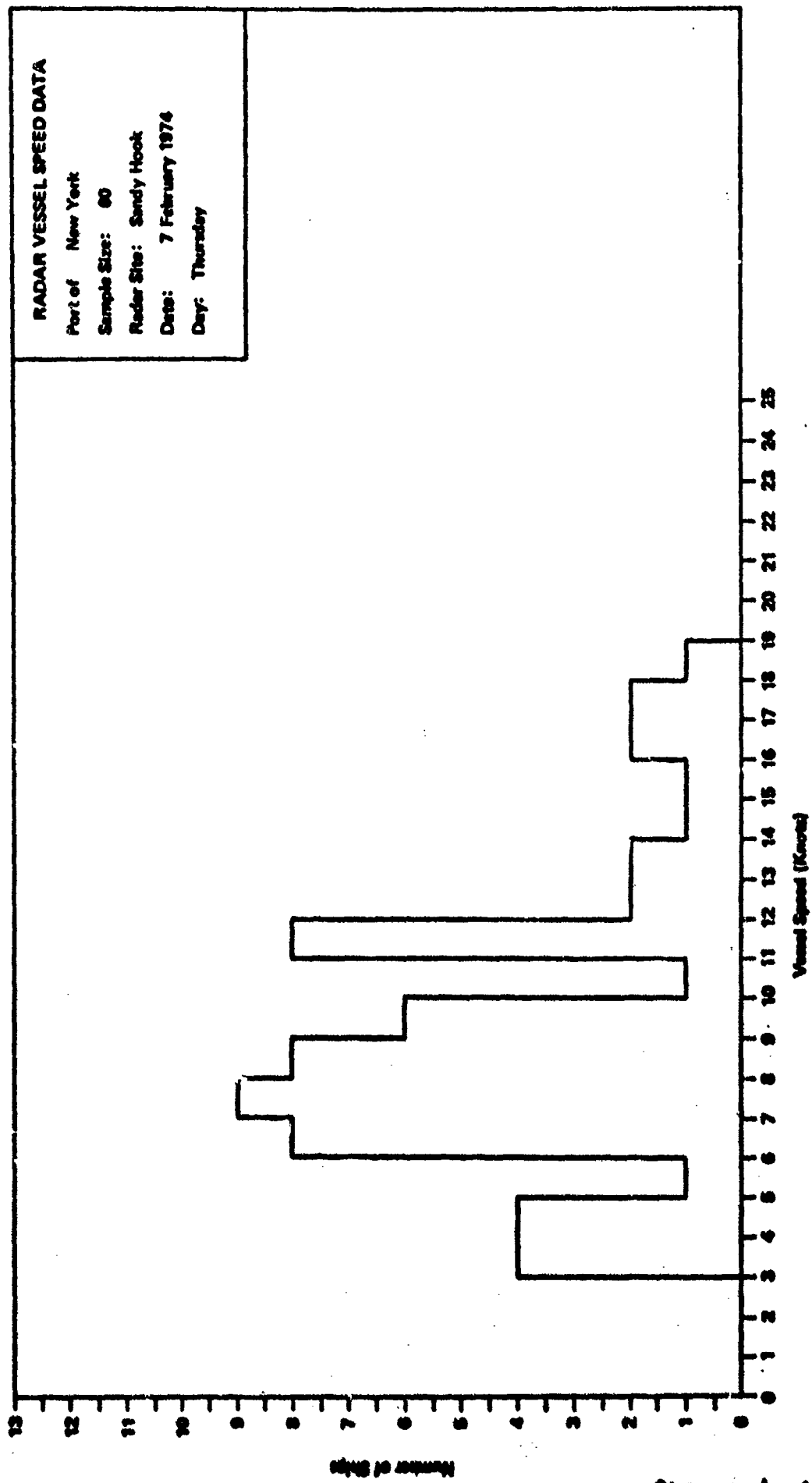


FIGURE 3-19. RADAR VESSEL SPEED DATA - PORT OF NEW YORK

3-27

09-3-284

PAGES 4-1 THRU  
 4-48 FOLLOWING  
 - MARK

51A



## DESIGN AND USE OF AID TO NAVIGATION PERFORMANCE MODEL

## 4.1 DESIGN APPROACH TO MODEL DEVELOPMENT

Our approach to the design of an AN performance model is to represent the navigator's and helmsman's behavior, traffic behavior, ship's equipment, and ship responses as observed at sea. To effectively do so we developed (designed and demonstrated) three stand-alone computer models: a fix model, a navigating and steering model, and a traffic capacity model, which provide output data corresponding to the three measures of effectiveness discussed in Section 3.

FIGURE 4-1 illustrates that the models can function either independently or in unison to evaluate AN performance. Thus, the effects of changing AN configurations can be studied in terms of one measure of effectiveness or from a composite, interactive approach. The connecting links between models are not computer links; they are meant to imply the iterative use of the models in analyzing and refining an AN configuration for a specific area. A fourth model, shown in FIGURE 4-1 by dashed lines, represents one further iteration of AN evaluation. This model would determine the economic return to the port for reduced traffic delays and increased safety. Feasibility of the economic model was only investigated in this effort; development has not started.

All three models in FIGURE 4-1 have been developed and made operational. Operation of both the fix model and the navigating and steering model has been evaluated for clear weather against CAORT and at-sea data bases. Section 5 of this report describes validation of these models. The traffic capacity model has been made operational at an elementary level to prove its feasibility. The model output data compare favorably to at-sea and ship simulator data. We have a high degree of confidence that, when fully validated, the models can be used to evaluate most AN performance questions.

The AN performance models developed by EA simulate the real world. As stated above, navigating, steering, and ship processes that have been observed or are known to exist at sea have been represented in the models. The models simulate or represent, in fast time, the evolution of actual processes occurring in real time at sea. Variations in these processes attributed to equipment differences, perceptual differences, and behavioral variations are entered in the models as probabilistic distributions of response. (See subsection 4.2 below). At any point in simulated time where a variety of possible behaviors or responses exists, the models randomly (or dependently for certain behaviors and processes) select a sample response from a predefined distribution of responses. Given this sample, the problem continues to update to the next point in time where another selection of behaviors or responses is possible. The models again randomly (or dependently) select a sample. This procedure continues until the simulated run is completed. (Random selection from defined distributions is the principal characteristic of a Monte Carlo model.)

Each fast time run of a model simulates the navigation of a ship once through the specified geographic area. Navigating the ship many times through the area is simulated by repeating the fast time runs, starting with randomly selected initial conditions and with each run randomly selecting samples from the predefined distributions. The resultant position fixes and track plots of each fast time run will differ by virtue of the random

MEASURES OF EFFECTIVENESS

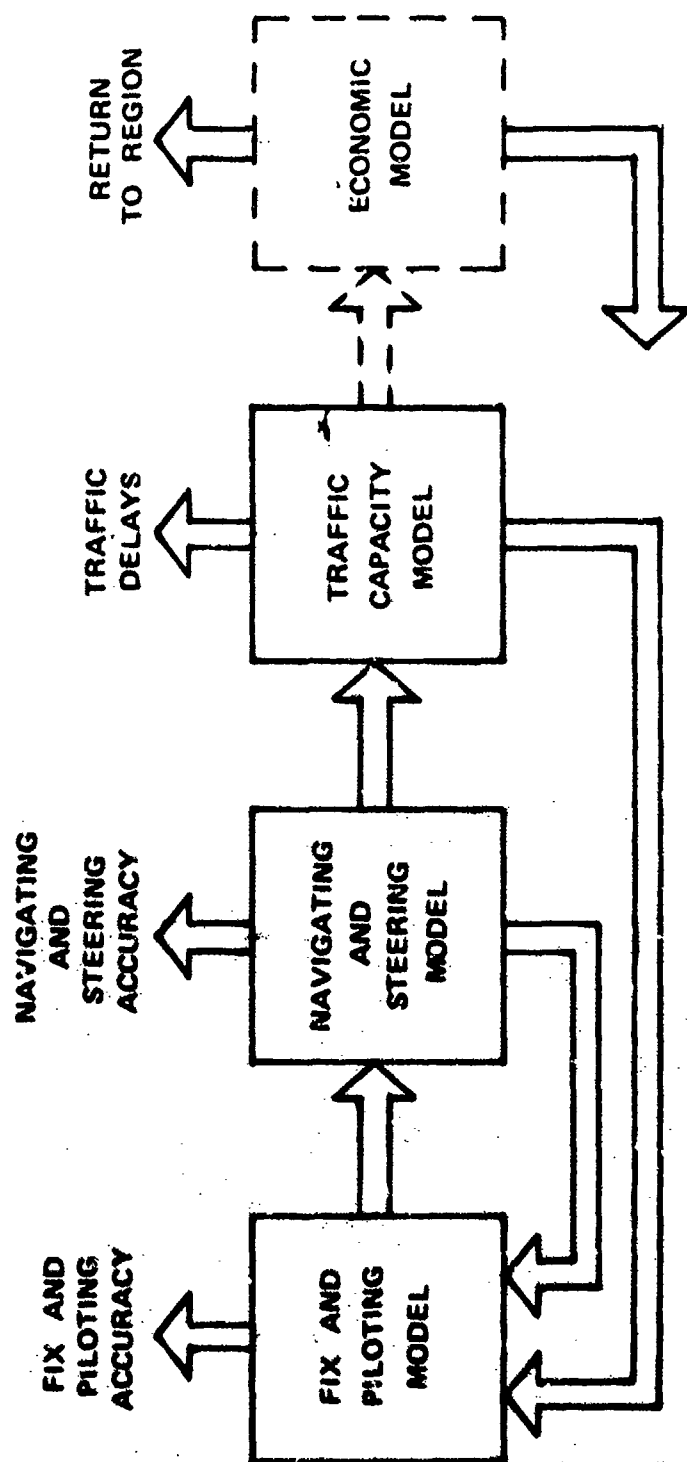


FIGURE 4-1. AN PERFORMANCE MODELS

selection from the distributions. The measures of effectiveness of the ANs are calculated by averaging the results of many fast time runs, as if many ships had been observed at sea. Data are represented as probabilistic variables by making many fast time runs and statistically combining the results.

The actual speed of the calculations for the fast time simulation of ship navigation is dependent on many factors such as the specific computer type, the complexity of the scenario, the desired decision-action logic, and the quantity of output requested. The model as programmed and run on a DEC System PDP 11-40 digital computer has been performed at 3 to 5 times faster than real time. That is 60 minutes of real time navigation has been simulated in 12 to 20 minutes. This fast time simulation has no effect on the physical processes being simulated, since all time dependent calculations are performed as though they occur at the real time interval. Fast time simulation means the computer can work through the calculations governing the real occurrence at a faster rate than the occurrence can take place in the real world.

The capability to simulate navigation in a wide variety of geographic areas with diverse ANs comes from the models' generalized modular design. A detailed review and analysis of both the navigator's behavior and AN use indicated that many processes and AN and RA characteristics were common, but that frequency of tasks, navigation accuracy required, and types of equipment used varied as a function of geographic area. (See Appendix B.) An important requirement was to assemble general purpose programs that could simulate navigating, steering, ship's equipment and ship's responses in a wide variety of geographic areas (scenarios) with diverse ANs and RAs, given alternate logic instructions, coefficients, and distributions. All three AN models have been structured to allow this flexibility.

Section 4.2 discusses the mean and distribution relationships used by the models and their sources. It also identifies which distributions or relationships require further data collection. Section 4.3 then describes the types of data that can be input to the models. These are AN configurations, AN design characteristics, scheduled traffic flow, and geographic area limitations. Section 4.4 discusses how the models operate, presents the output capabilities of all three models, and provides examples of output data for the three models. (For a full technical description of the models' design and operation, see Appendix A.)

## 4.2 EQUIPMENT ERROR, PERCEPTUAL DIFFERENCES, AND BEHAVIORAL RESPONSE

Variable distributions and mean relationships programmed in the model fall into three categories: equipment, perception, and behavior. The distributions about the mean may be Gaussian, log Rayleigh, or defined only as histogram points. These distributions may represent variations about a zero error mean or about a displaced mean.

### 4.2.1 Equipment Error

Equipment error distributions are presently limited to five equipments:

- Gyro or compass
- Radar range and bearing
- Position receivers (LORAN-C)

- Radio direction finder (RDF)
- Speed log (if available on ship)

Errors that may result from use of these equipments are attributable to both their mechanical or electrical error plus the navigator's errors in reading the instrumentation and roundoff errors. TABLE 4-1 lists typical errors which may exist between equipment on alternate ships plus the contribution of the navigator. All errors are assumed to be zero mean with Gaussian distributions. Note in this table that the human contributions can be substantial both in terms of interpretation and roundoff. Also note that the gyro error affects many other equipments.

The modeling of equipment and human errors must be handled cautiously in the Monte Carlo model. Equipment errors are usually randomly selected for each run at the beginning of the run and held constant during the run. Human interpretation and roundoff errors are randomly selected from their respective distributions for each observation. If desired, the model can allow the gyro error to change as a function of time and bearing.

#### 4.2.2 Human Perceptual Error

Human perceptual errors are used in the models when an AN is being detected or when the navigator is estimating his position from visual information alone. Four types of perceptual means and distributions are required for various aid types and weather conditions:

- Visual detection
- Detection on radar PPI
- Visual bearing estimation
- Visual range estimating

TABLE 4-2 lists the required conditions for which the mean value relationships exist and are provided in the model. TABLE 4-3 lists the variable distributions about the mean values. Both tables indicate the mean functions and distributions that remain undefined and that must be determined in the future at sea and on ship simulators. We wish to stress that we have demonstrated that this type of data can be collected at sea and in simulators and that, in the time and cost framework of Phase II, the additional data collection is highly feasible.

Some empirically based data are now available for defining the mean visual and radar detection ranges. The basic relationships that apply and their sources are indicated in TABLE 4-2. However, there are two single exceptions to the defined relationships: (1) multicolored buoys and (2) flash tube lights. The contrast relationship of black-and-white sea buoys has not yet been established to allow a mean daytime detection range to be determined. At-sea experience and recent photographs taken at sea show that these particular buoys are extremely difficult to detect at long ranges (2 to 4 miles) if any sea is running. Although these buoys form only a small number of total buoys in U.S. waters, their critical contribution to harbor approach places them above many others in importance.

Detection and localization of flash tube lights are also not well defined. Although studies have indicated that flash tube ANs may be perceived as having higher intensity, the ability to estimate the aid's range and bearing seem to be impaired. These relationships must be explored in the near future if more of these aids are to be deployed.

TABLE 4-1  
EQUIPMENT ERRORS

	EQUIPMENT ERROR	HUMAN INTERPRETATION ERROR	AN MODEL ERROR
	STD DEV	STD DEV	STD DEV
GYRO (HEADING) <sup>1</sup>	+0.75 deg	1 deg roundoff	* +0.75 deg 1 deg roundoff
GYRO (PELORUS) <sup>2</sup>	+0.75 deg	+0.8 deg & 1 deg round off	* +1.06 deg 1 deg roundoff
RADAR (RANGE) <sup>3</sup>	+ 0.02 NM to 1% scale	+ 0.014 NM & 0.01 NM roundoff	+0.024 NM to (1% scale + 0.14) *0.01 NM roundoff :
RADAR (BEARING) <sup>3</sup>	+ 1 deg plus gyro error	+ 0.6 deg 0.5 deg roundoff	* +1.39 deg 0.5 deg roundoff
LORAN-C <sup>4</sup>	+ 0.25 NM geographic dependent		+ 0.25 NM geographic dependent
OMEGA <sup>5</sup>	+1.0 NM (day) +2.0 NM (night)		+1.0 NM (day) +2.0 NM (night)
RDF <sup>6</sup>	+ 5 deg plus gyro error	1 deg roundoff	* +5.05 deg 1 deg roundoff
SPEED LOG <sup>7</sup>	+ 1% full scale (deep water)	0.1 knot roundoff	+1% full scale 0.1 knot roundoff (deep water)

1. Sperry Mk 227 average sea condition increase to +1.5 deg with speed and latitude comp
2. Human error function from MARAD experiment at CAORF
3. Sperry Mk 16A, human error function from MARAD experiment at CAORF
4. Raytheon LORAN C receiver
5. Raytheon OMEGA receiver
6. Raytheon RAY-DF-20, +5° beacons, +4° marine, +3° broadcasts.
7. Sperry, SRD 301,

\*Increase if gyro compass has no speed or latitude compensation, gyro error = 1.6

\*\*Total std dev calculated as the square root of the sum of the contributing std deviations squared

TABLE 4-2. MEAN VALUES FOR NAVIGATION PERCEPTUAL TASK

	Unlighted AN Day	Lighted/ AN Day Night	AN in Limited Visibility	AN in Sea State
Visual Detection	Duntley 1.2 Nomogram	Allard's 2.3 Law	Allard's 2.3 Law	0
Radar Detection	Radar Reflector Performance 2.4	NA	NA	0
Visual Bearing Estimation	MARAD Data CAORF5 Figure 4-2	0	NA	NA
Visual Range Estimation	MARAD Data CAORF5,6 Figure 4-4	NA	NA	NA

0 - Relationship presently not  
quantified

NA - Not applicable

Sources For Equations:

1. USCG Report "On Daytime Ranges of Buoys", LCDR G. P. Clark, 1971
2. USCG Report CG-250-33 "Performance Characteristics of Buoys"
3. USCG Report CG-250-12E "Luminous Intensities of Navigational Aids," USCG Report CG-250-33"
4. IALA May 1966 "Method of Calculating the Maximum Range of a Radar Reflector"
5. MARAD Special Studies for Restricted Waterways Experiment at CAORF
6. Gilinsky, A. S., "Perceived Size and Distance in Visual Space," Psychological Review 1951, 58, 460-432

TABLE 4-3 STANDARD DEVIATIONS DISTRIBUTIONS ABOUT THE MEAN VALUES FOR NAVIGATION PERCEPTUAL TASKS

	Unlighted AN Day	Lighted AN Day Night	AN in Limited Visibility	AN in Sea State
Visual Detection	+ 0.05R <sup>1</sup>	+ 0.05 R <sup>1</sup>	+ 0.05 R <sup>1</sup>	0
Radar Detection	+ 4 db <sup>2</sup> Signal Level	NA	NA	0
Visual Bearing Estimation	MARAD Data CAORF <sup>3</sup> Figure 4-3	0	NA	NA
Visual Range Estimation	MARAD Data CAORF <sup>3,4</sup> Figure 4-5	0	NA	NA

1. Weber criteria 1 = 0.14 1 at 1.5 std deviation. R = range. Comsweet and Pinsile, "Luminous Discrimination of Brief Flashes Under Various Conditions of Adaptation" Applied Journal of Psychology, London 1976, 294-310

2. Baker, C. H., "Man and Radar Displays", Chapter 7, pg. 66

3. MARAD Special Studies for Restricted Waterways Experiment at CAORF

4. Vincent, R. J., et al "Distance Discrimination in a Simulated Space Environment" Perception and Psychophysics, 1969, 5, 235 - 238

0 - Relationship presently not quantified

NA - Not applicable

Visual estimating of bearing and range relationships have recently been obtained during MARAD-sponsored research at CAORF. These data, vital for model operations, show the potential impact CAORF can have on the AN modeling program. Preliminary data from these experiments indicated in FIGURES 4-2 through 4-5 show the high degree of impact these data have in providing values for the modeling process. Both the bearing estimation and range estimation display mean biases. Data in FIGURE 4-2 indicate that pilots estimate that small angles relative to the bow are greater than the actual values while angles between 40 and 85 degrees are estimated to be less than actual values. Mean distance estimates in FIGURE 4-4 always appear to be greater than actual distances. However, a theoretical fit to these data does not appear appropriate. The failure to fit experimental values highlights the importance of gathering data for these functions either at sea or on simulators. Additional data on range estimating ability can be gathered during simulator experiments in Phase II.

The standard deviations of bearing estimation appear to be well behaved. The deviation for small angles (1 to 3 degrees) is equal to the value of the angle itself. The standard deviation grows to over 10 degrees at 85-degrees relative bearing.

The standard deviations for range estimation grow rapidly with an increase in range. Experimental data in this case differ widely from theoretical projections. Additional data points in this distribution can be gathered in Phase II to further define this function.

Bearing and range estimation data in FIGURES 4-2 through 4-4 represent performance for daytime conditions. Similar data will be compiled either at sea or on CAORF under nighttime conditions to complete model development. These data should also be collected for flash tube lights if the Coast Guard anticipates a wide distribution of this type of buoy.

One note of caution is to be applied to FIGURE 4-3 in reference to standard deviation of bearing estimation. These data represent observations of a single buoy. The determination of bearing errors of two or more buoys with similar true bearing involves a rather complex correlation of errors attributed to each buoy. Thus, bearing errors in multi-aid situations may not necessarily be selected directly from FIGURE 4-3. Correlation of bearing errors is discussed in Appendix A.

#### 4.2.3 Behavioral Variations

The final set of distribution functions required for the model represents variable behavioral responses. These responses are attributable to both pilot and helmsman behavior. They include:

- Maneuver completion time
- Course corrections in channels
- Error threshold for maneuver

Maneuver completion time is the time required for the helmsman to steady the ship onto a new heading for a given course change. FIGURE 4-6 shows the distribution of maneuver completion for a 2-degree course change. These data were measured on a 30,000-dwt tanker at sea. As might be expected, most turns are completed rapidly (30 to 40 seconds). Few turns are completed faster than this. Over a third of the turns are completed slower than the norm (i.e., take more than 40 seconds to complete).



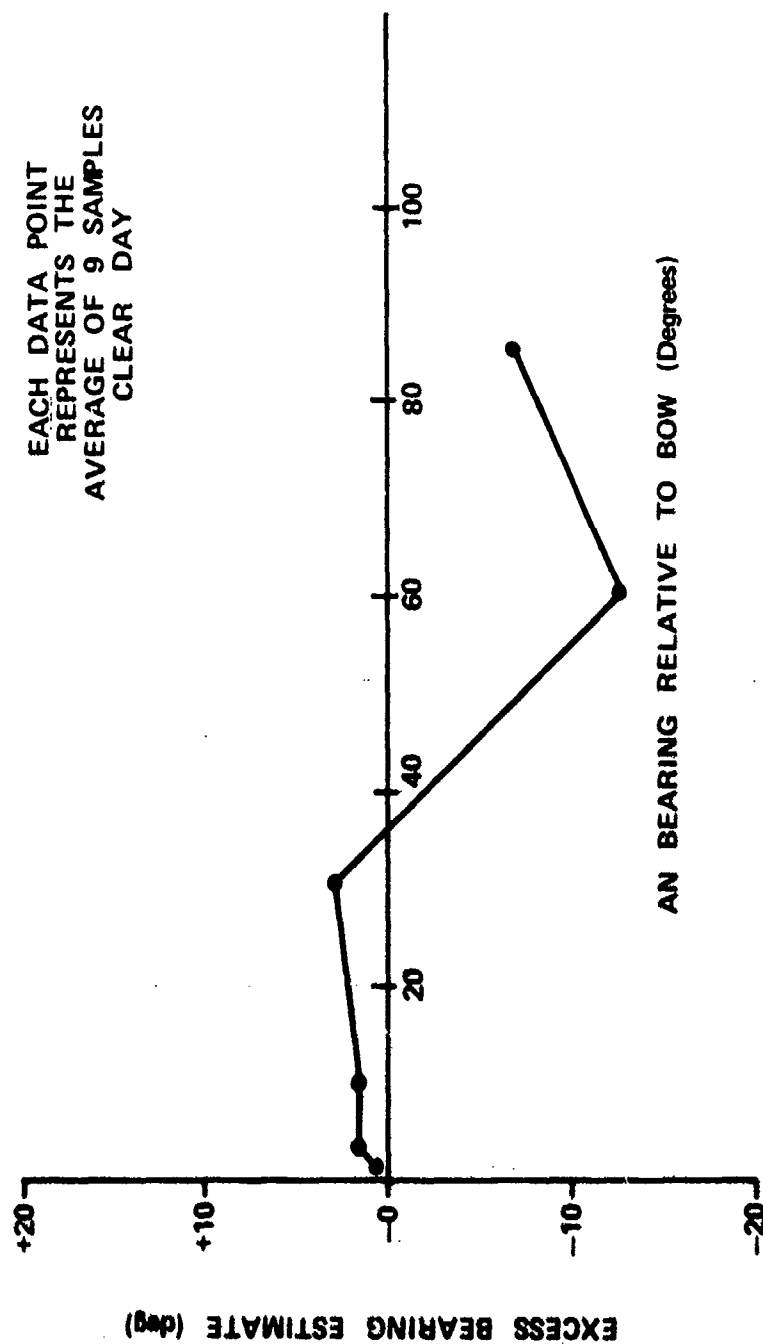


FIGURE 4-2. VISUAL BEARING ERROR, MEAN DISPLACEMENT FUNCTION,  
SINGLE BUOY (CAORF DATA)

EACH DATA POINT  
REPRESENTS THE  
AVERAGE OF 9 SAMPLES  
CLEAR DAY

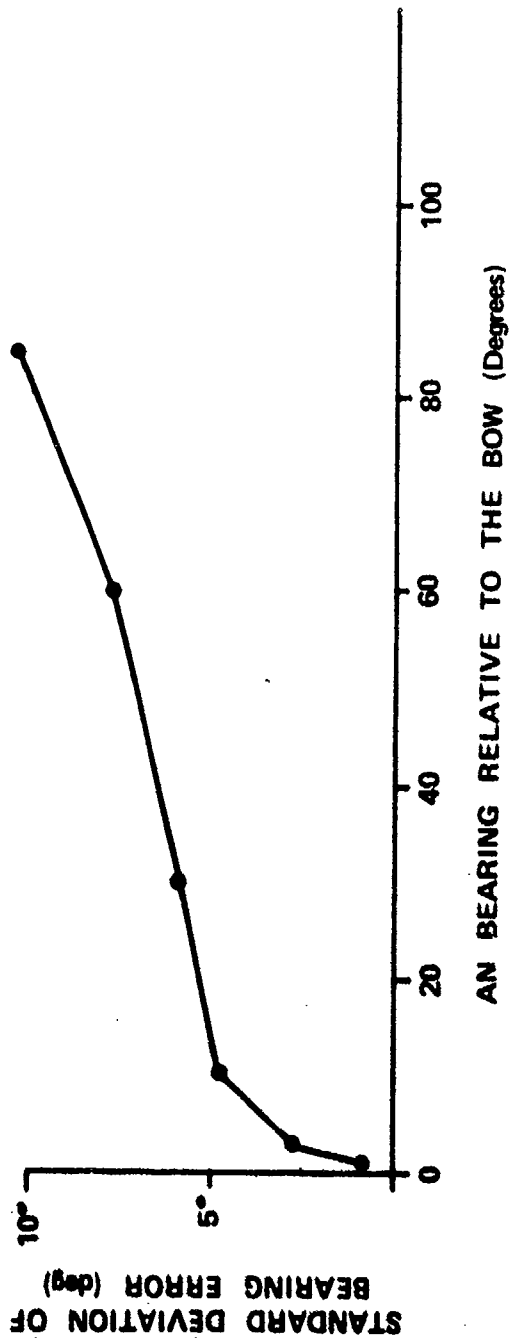


FIGURE 4-3. VISUAL BEARING ERROR, STANDARD DEVIATION FUNCTION,  
SINGLE BUOY (CAORF DATA)

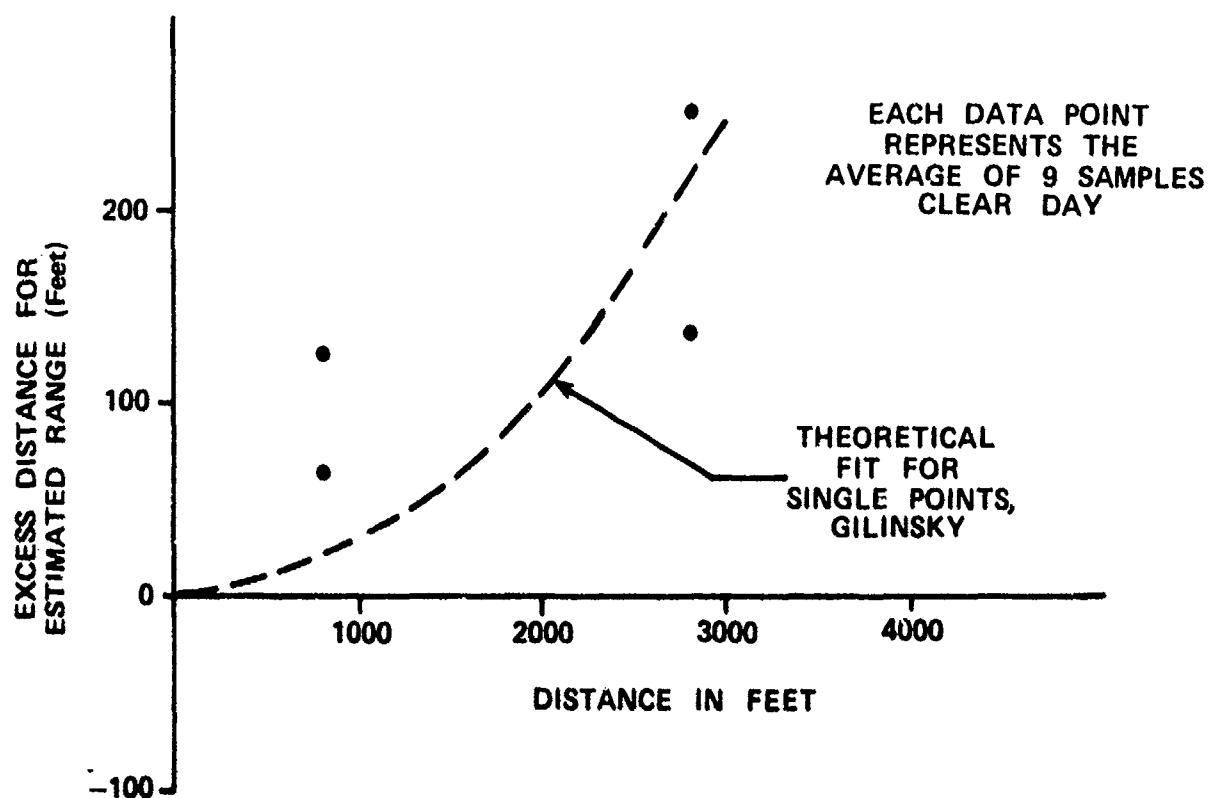


FIGURE 4-4. VISUAL RANGE ERROR, MEAN DISPLACEMENT FUNCTION, SINGLE BUOY (CAORF DATA)

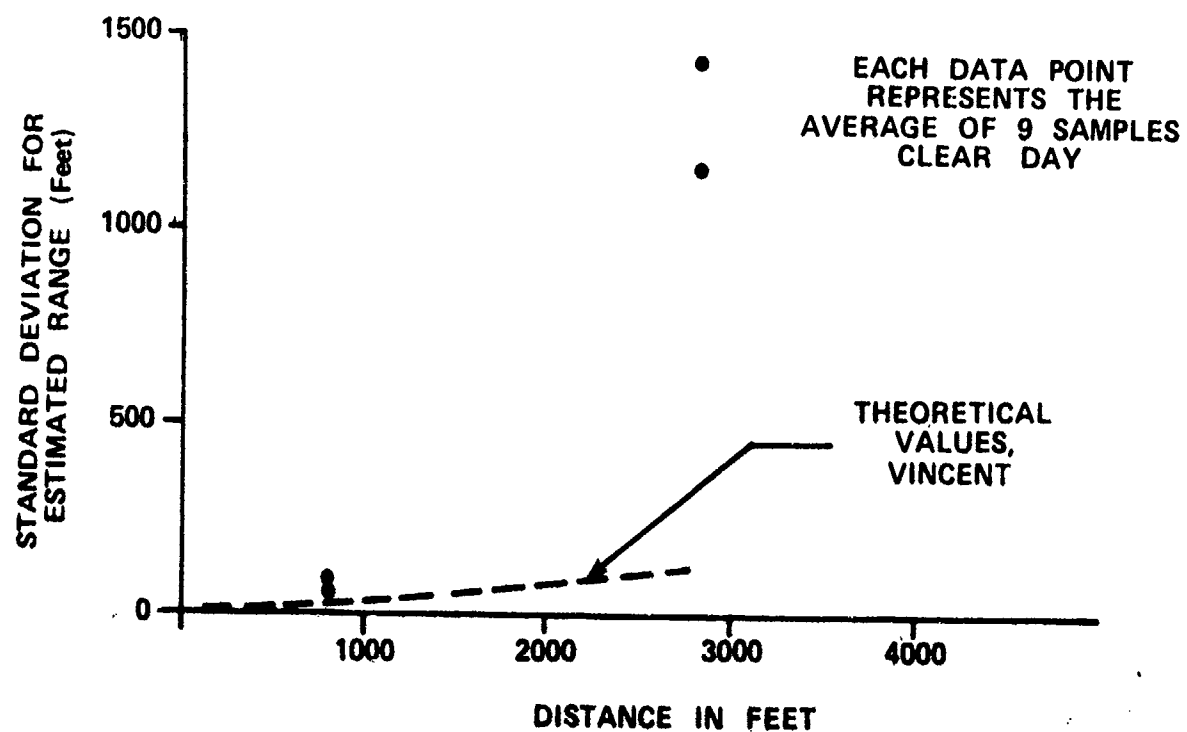


FIGURE 4-5. VISUAL RANGE ERROR, MEAN DISPLACEMENT FUNCTION, SINGLE BUOY (CAORF DATA)

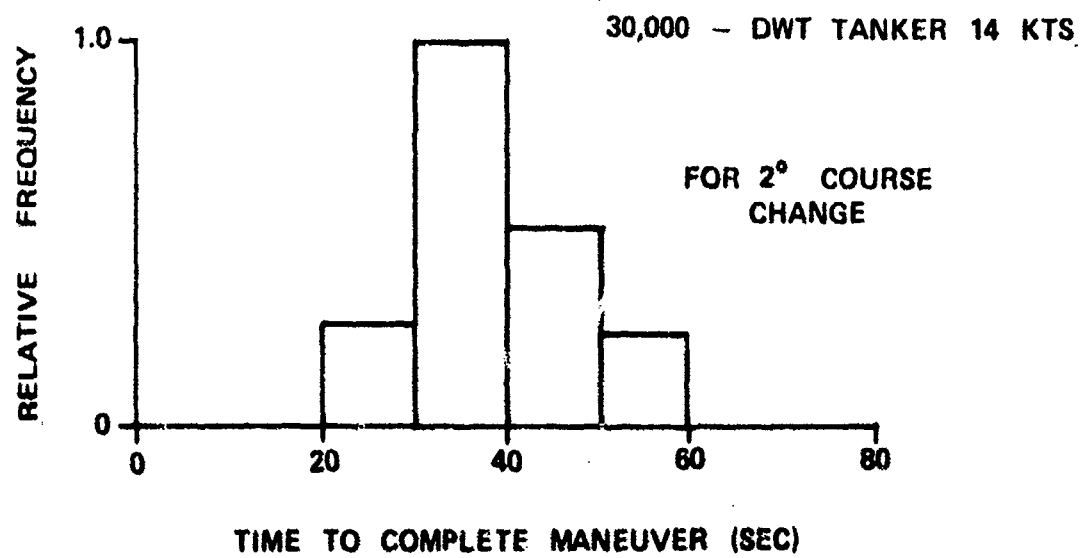


FIGURE 4-6. DISTRIBUTION OF TIME TO COMPLETE MANEUVER FOR A 2-DEGREE COURSE CHANGE

Data in FIGURE 4-7 for the same ship indicate that the average completion time rises more or less linearly with the magnitude of the course change. Curves in FIGURES 4-7 and 4-8 will be expected to move laterally without changing shape for vessels less maneuverable. These data are easily obtained at sea or on a ship's simulator.

The distribution of control behavior in channels indicates a more highly stereotyped behavior. Data in FIGURE 4-8 indicate that course and track control changes are achieved primarily by 1-, 2-, or 3-degree course changes. The predominant change is 2 degrees. Instances could be found where two course changes of 2 degrees were ordered in succession, if correction of the error situation was not satisfactory.

The final behavioral distribution used is that cross channel position or velocity when corrective orders are given. FIGURE 4-9 shows the relative frequency of corrective course orders as a function of estimated cross track position. Two strategies are clear in these data. The 3/4-cross track position appears to be the line that the pilot does not wish to cross. He initiates corrective orders left when he reaches or is about to cross this line. Many orders are also given when ship is midchannel. Steer right orders are given to prevent crossing to the left side of the channel, to compensate for current and wind, and to move the ship right or left in the channel to aid in making the next turn. The data in FIGURE 4-9 are necessarily limited by the short time dedicated to collecting the data at sea. There were relatively few corrective course orders given while transiting the channels. Review of the restricted waterways experimental plan at CAORF indicates that data similar to FIGURE 4-9 will soon be available from that experiment. The larger data pool available in the experiment should aid in defining the width of the distributions in FIGURE 4-9.

### 4.3 DATA INPUTS

#### 4.3.1 AN and RA Characteristics

ANs and RAs have eight general characteristics that contribute to defining an AN configuration and that potentially affect, or provide information to, the navigation process. These characteristics (discussed in Appendix B) are inputted to the fix and navigating and steering models when describing the ANs or RAs for a particular geographic area. These characteristics are:

- Visual detection range (daymark or light) – daytime, nighttime, limited visibility, and sea state
- Radar detection range – ideal weather and in sea state
- Elevation of aid above mean water level
- Charted position of aid
- Potential error in floating aid position
- Potential error in RA position signals at receiver output
- Aid identification
- Flash characteristics (strobe versus incandescent)

(Identification characteristics (color, size, flash code, and shape) are not inputted into the model, since it is assumed that ANs will be properly identified by the navigator.)

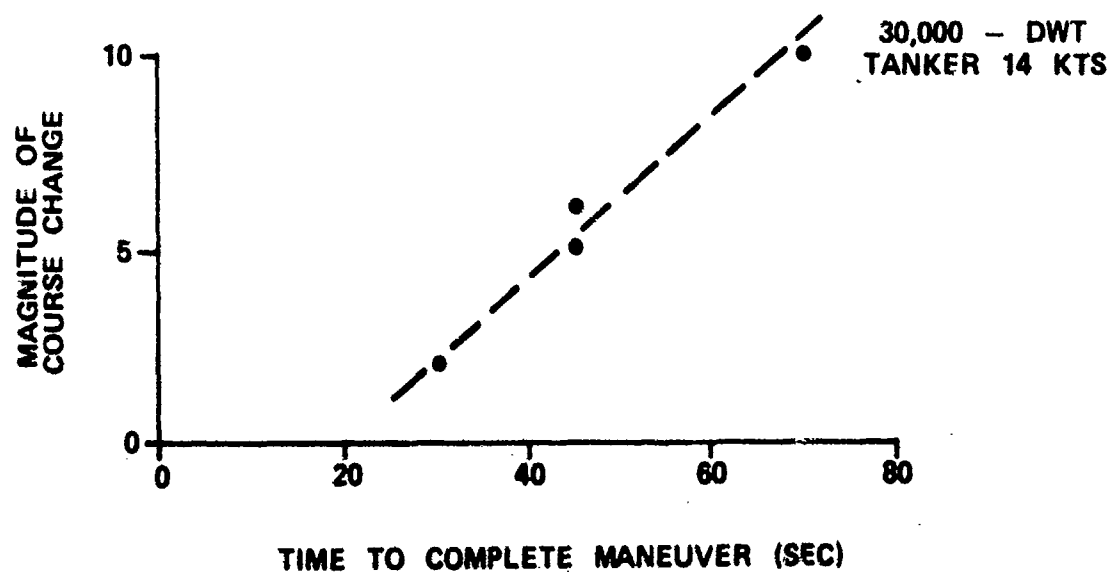


FIGURE 4-7. AVERAGE TIME TO COMPLETE MANEUVERS VERSUS COURSE CHANGE

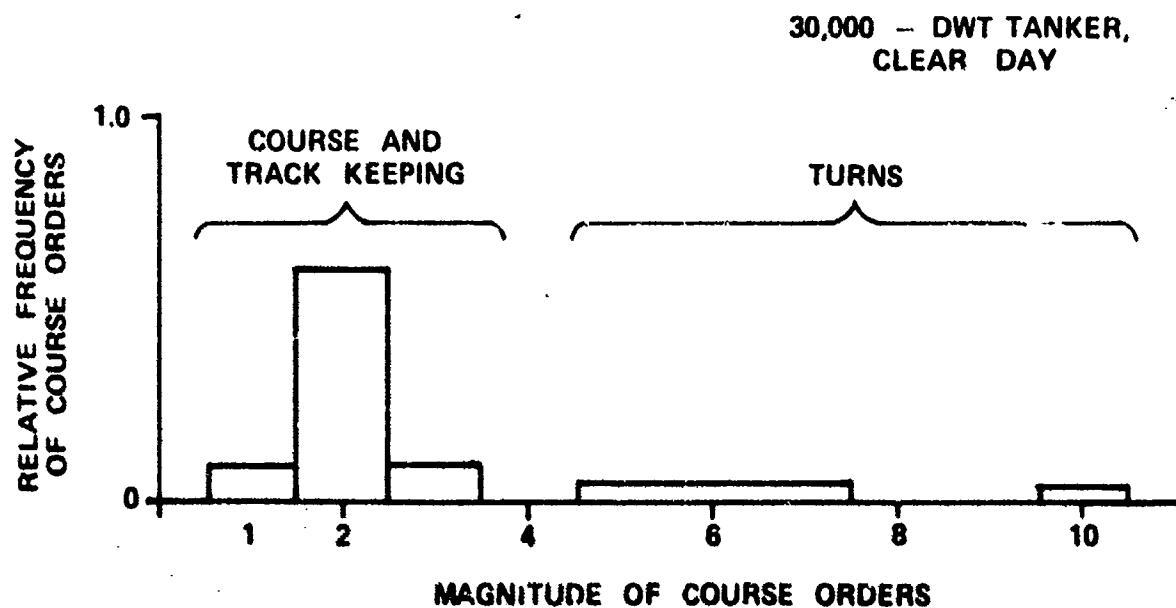


FIGURE 4-8. DISTRIBUTION OF MANEUVERING ORDERS



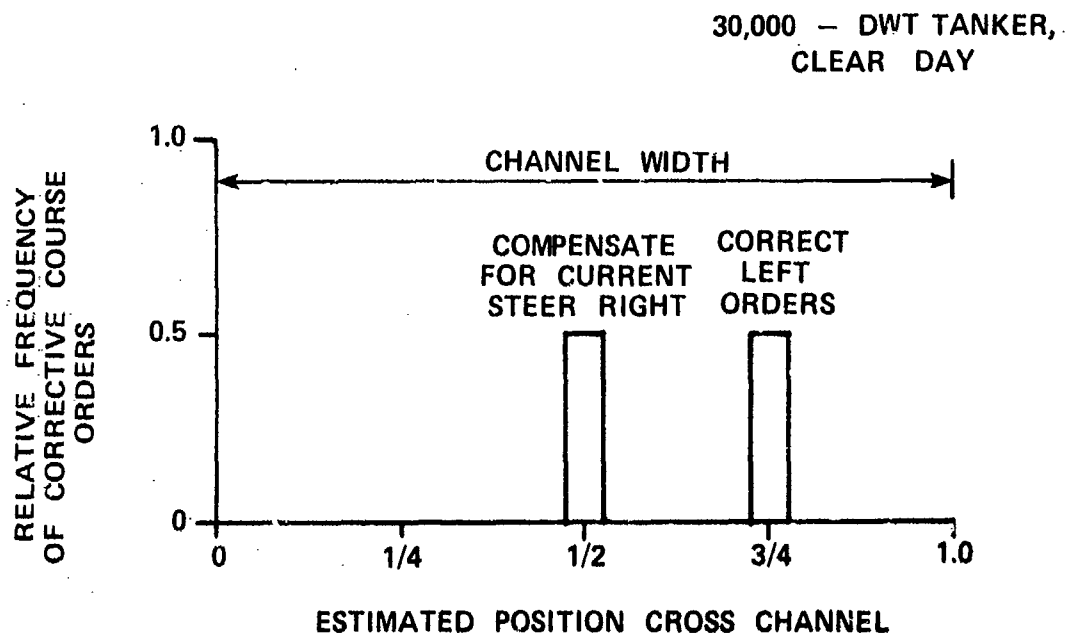


FIGURE 4-9. ESTIMATED POSITION AT ISSUANCE OF ORDERS

#### 4.3.2 Navigation Processes

The fix and navigating and steering models simulate seven general navigating and steering processes. These processes contain the majority of the behavioral variations, perceptual variations, and equipment error functions for the models. Each process can be modified via input routines for specific geographic areas. (See Appendix B.) These processes are:

a. Detect ANs and estimate bearing and range using radar, pelorus, and visual perception.

b. Estimate, in the following terms, ship's position and ship's state from AN estimated ranges and bearings, RA positions, and dead reckoning position:

- Along track position
- Cross track position
- Certainty of fix
- Ship's speed along and cross track
- Current effects
- Wind effects
- CPA to hazards

c. Make decisions and select actions in the following terms:

- Position, turn rate, and course made good acceptable?
- Fix certainty acceptable?
- AN configuration optimum for fix?
- CPA to hazards acceptable?
- Has specified aid been reached ?
- Has a specified along track position been reached?

d. Initiate actions in the following terms:

- Determine and order new course, rudder angle, or rpm to achieve goals
- Increase or decrease fix frequency
- Take fix immediately
- Take fix to specified aid
- Use specific equipment or method for fix
- Monitor orders

e. Steer ship to maintain course

- Order rudder to initiate desired turn rate
- Order rudder to stop turn rate on course
- Complete course change in stated time

- Comply with rudder order
  - Correct for wind and propeller-induced yaw moment
- f. Maintain dead reckoning track
- g. Simulate ship hydrodynamics
- Respond to helm orders
  - Respond to engine orders
  - Update position in geographic coordinate
  - Simulate many vessels.

#### 4.3.3 Traffic Capacity

Traffic interactions and delays in channels are modeled only in the traffic capacity model. This model simulates, in fast time, many vessels moving simultaneously at various speeds through a specified waterway system. The variable distributions in the model are port arrival, berth departure times, and vessel maneuvering speeds. All vessels follow a general set of rules while moving along specified paths. These rules are:

- a. Each vessel slows in turns if required.
- b. A vessel may overtake and pass slower vessels only in specified channel sections and only if the maneuver can be completed in that section.
- c. Two-way traffic is permitted only in certain channel sections.
- d. Each vessel maintains a safe interval behind the vessel in front (based on each ship's stopping capability).
- e. A vessel cannot enter the channel system until there is sufficient room.

#### 4.4 OPERATION OF MODELS AND OUTPUT CAPABILITIES

All three AN performance models - fix accuracy, navigating and steering, and traffic capacity, provide the capability of representing the measures of effectiveness in a number of formats and as trends in a number of measured variables. For instance, the navigating and steering model can output probabilistic plots of swept width data, rudder activity, fix variance, cross track velocity, course made good, etc. All of these measures can provide insight into the navigation accuracy achieved with one configuration of ANs versus another.

##### 4.4.1 Fix Model

The fix model was assembled as a stand-alone model for the purpose of rapidly evaluating the order of magnitude of fix accuracy obtainable for AN configurations. The variable distribution of equipment errors, interpretations roundoff, and perceptual errors in estimating position are simulated in this model. Variability of detection range is not simulated in this model. All aids are considered detected as they cross their mean

threshold range for detection (day, night, or limited visibility). Fix accuracy can be evaluated using particular equipments, combinations of equipments, visual perception alone, or visual perception plus equipment data.

The fix data may represent a static or dynamic fix accuracy. A static fix represents the accuracy achievable if the vessel were placed at a position with no history of previous motion. A dynamic fix represents the accuracy achievable when the navigator adds DR information to his position estimate. FIGURE 4-10 shows the relationship of the various fix estimating routines as fix data are combined to determine static and dynamic fixes.

The determination of position using bearings, ranges, and positional data from equipment is a process that involves: selecting observation samples from equipment error distributions, applying interpretation and roundoff errors, then crossing ranges and bearings, and selecting the maximum probable position or least risk position as the estimated position. These processes are well known and represent most fix tasks performed at sea, in coastwise waterways, and in port approaches. However, estimating position in restricted waters using visual information alone is a little known process. Our approach has been to obtain opinions of how this is done from pilots, review fix accuracy data observed at CAORF, and synthesize a method of visually perceiving a position from observed bearings and ranges to ANs.

Basically, we model visual fixing techniques identical to those used with equipment data. Estimated bearings and ranges to ANs are crossed; the maximum probable position or least risk position is selected as the estimated position. The model provides mean error and distributions of error functions for both visual estimation of bearings and ranges to ANs. However, selecting observed bearings and ranges from these functions only initiates the perception model process. All observed AN bearings (actual bearing plus mean plus error sample selected) are scanned to see if any lie close to each other in bearing. If this is so, the bearing errors of these particular aids are correlated (i.e., made nearly equal) so that the relative angle between them is approximately correct. This correlation prevents the random observation of one AN to the right of another aid when it is actually left. Thus, our pilot seldom misinterprets if one aid lies left or right of another. This is a good assumption for professional pilots, but may not apply to the recreational boater or to vessels with low heights of eye. The correlation function may be appropriately degraded in these cases.

The correlation of bearing errors also ensures that the pilot sees two aids nearly in line when they in fact line up in bearing. This ensures that the pilot is given an accurate line of position when he crosses the line or maneuvers on a range. The correlation of bearing errors also depends on the relative distances of the aids from the observer. This function causes ANs viewed from a high bridge position to take on the sensitivity in bearing equivalent to range lights as described in reference 18. FIGURE 4-11 shows that vertical angles, which play an important part in range sensitivity, also play an important role in view of ANs on the water. Our initial correlation function provides a continuous gradation of correlated AN errors from the in-line condition to independent observations when ANs are more than 10 degrees apart in bearing.

Estimated position from visual perception is determined by crossing the observed bearings to ANs whose bearing errors have been correlated for relative distances and bearings. Appendix A describes the above process in more detail.

A particular advantage of the visual fix process outlined above is that position can be estimated from a totally random geometry of buoys. Although ANs are not actually placed at random, geometries of aids become very complex in and about turns so that a fix

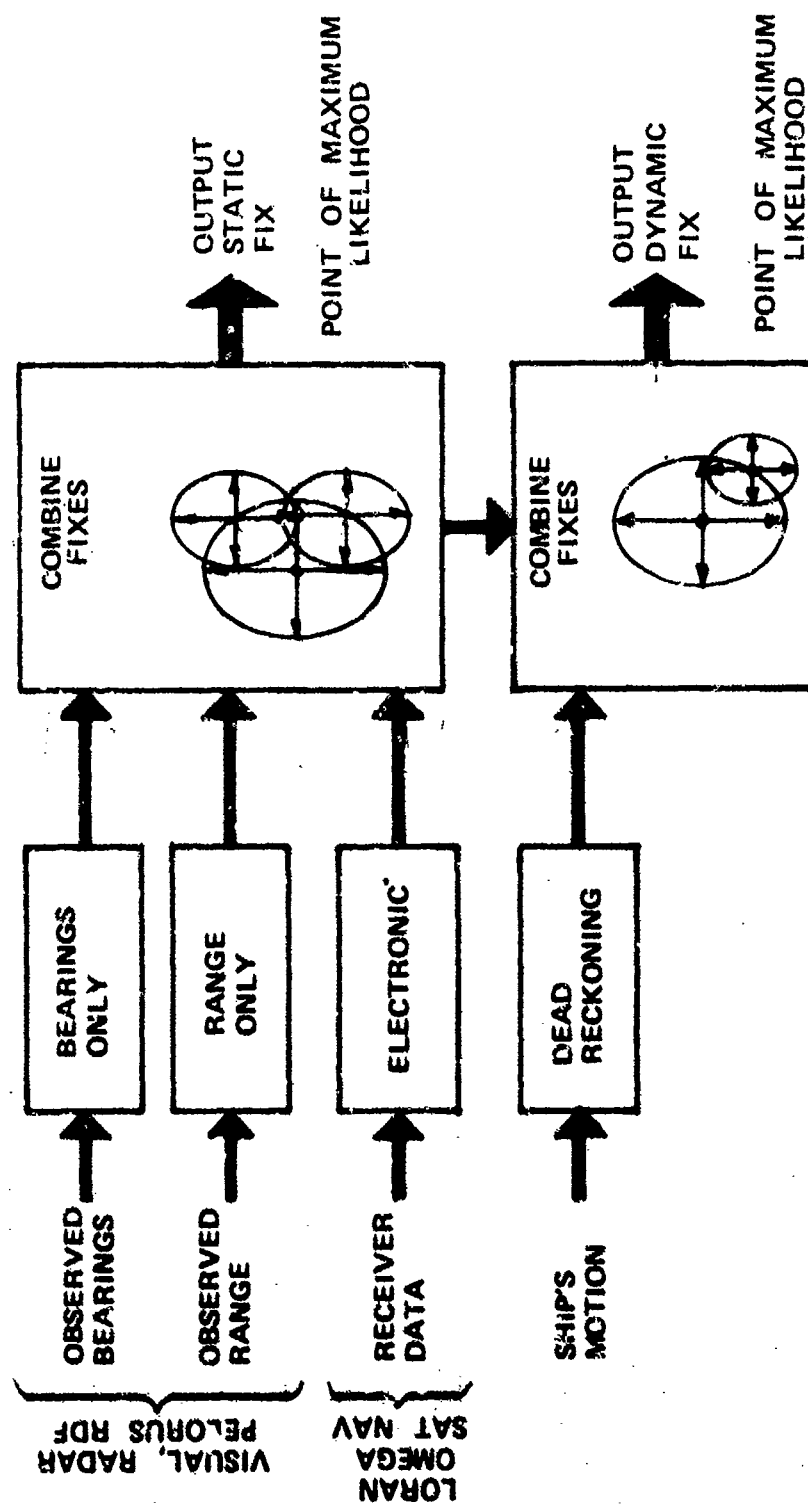
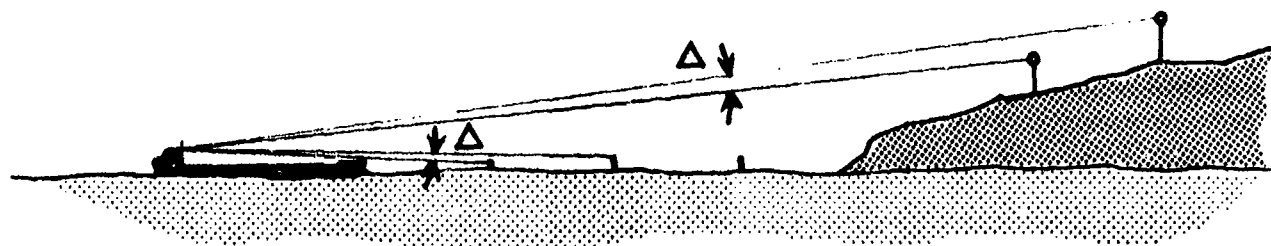
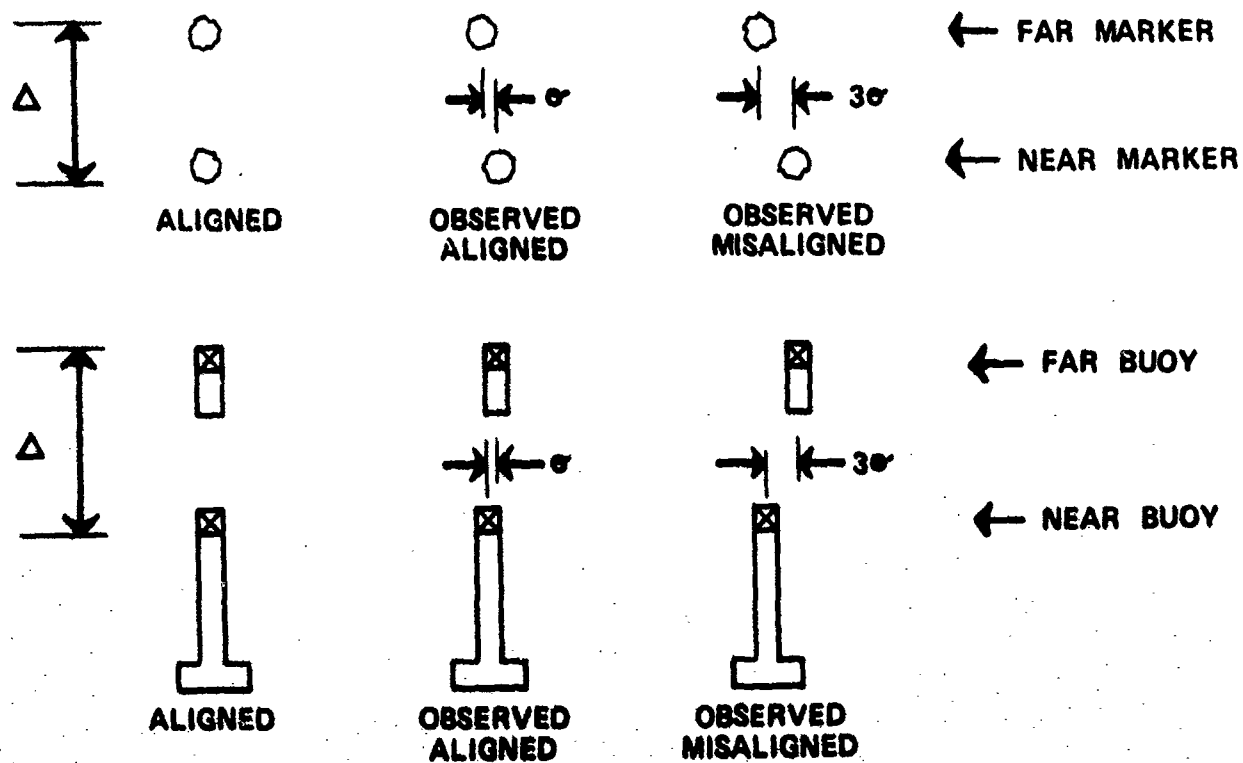


FIGURE 4-10. FIX AS INDEPENDENT AND DEPENDENT OBSERVATIONS



### VERTICAL ANGLES FOR RANGE LIGHTS AND BUOYS



$$\sigma = 0.172 + 0.038 \Delta \text{ FOR } 4.47 \leq \Delta \leq 17.19 \text{ MIN OF ARC}$$

$$\sigma = 0.344 + 0.028 \Delta \text{ FOR } \Delta \geq 17.19 \text{ MIN OF ARC}$$

$\sigma$  = STD DEVIATION OF BEARING DIFFERENCE FOR OBSERVED ALIGNMENT

$\Delta$  = VERTICAL VISUAL ANGLE

FIGURE 4-11. CORRELATION OF BEARING ERRORS

model that addresses only unique placements of ANs would not generally apply to at-sea problems.

During the design and development of the fix model, three versions of the fix model were assembled and made operational. Each of these models addresses unique questions regarding fix accuracy. They are:

a. Fix Accuracy Model, Static. This determines the probability that a pilot will estimate his position to be other than his actual position. This model answers the question: given a set of aids, what is the accuracy with which a pilot can determine his position? The output represents a static fix only.

b. Piloting Model, Static. This determines the maximum probable or least risk position of the ship. The model answers the question: given a set of observations, what is my position? The model also determines the pilot's confidence in his estimated position. This model is used in the navigating and steering model as a subroutine to determine estimated position before deciding on and initiating actions. Output data provide insight in the fixing process used by the pilot.

c. Piloting Model, Dynamic. This is identical to b above, except that a DR fix is considered when selecting the maximum probable position. Output data provided insight into the possible effects of DR on the navigation process.

The fundamental differences in these models is the interpretation of the results. Model a. represents the average behavior of a large group of pilots placed in the same position; models b and c represent a single fix determination by the pilot given his "observed" set of data (bearings, ranges, etc).

The output data from fix models a, b, and c are fundamentally the same. Three data formats are available: mean plus standard deviation in cross and along track position two-dimensional map of the probabilities of position; and continuous indication of cross track error or along track error as a function of distance along the track. FIGURE 4-12 illustrates a typical output data sheet for fix model a. In this particular case, the fix represents the accuracy of estimated position for visual perception of three floating ANs. This sheet illustrates the mean and standard deviation of possible estimated positions and a two-dimensional map of the probability of estimated positions. The standard deviations of along and cross track estimated positions are calculated as 14.3 yards and 27.9 yards, the square root of the variances (lower right-hand corner of FIGURE 4-12). These values were calculated from the data which appear in the grid map above. The key drawing indicates the location of the grid and true dimensions relative to the bridge of the ship. For this case, each block of the grid is 10 by 10 yards. Data values in the grid represent the probability of estimating the ship's position to be somewhere in the block. Isobars of 0.01, 0.02, and 0.03 probability have been drawn to emphasize that the resultant fix is not symmetrical to the cross and along track axes. Appendix A discusses the derivation of the two-dimensional map of probabilities and rationale behind the method.

The third format for presenting fix accuracy data is to represent the standard deviation of cross or along track error as a function of distance along a track. FIGURE 4-13 shows the position of a track relative to eight ANs. FIGURE 4-14 shows the cross track standard deviation for fix accuracies calculated along the track. Data have been calculated for three levels of visibility: 1/4, 1, and 4 nautical miles.

The value and flexibility of this third format have been demonstrated by programming the fix model in a desktop calculator that generated the curves in hard copy.

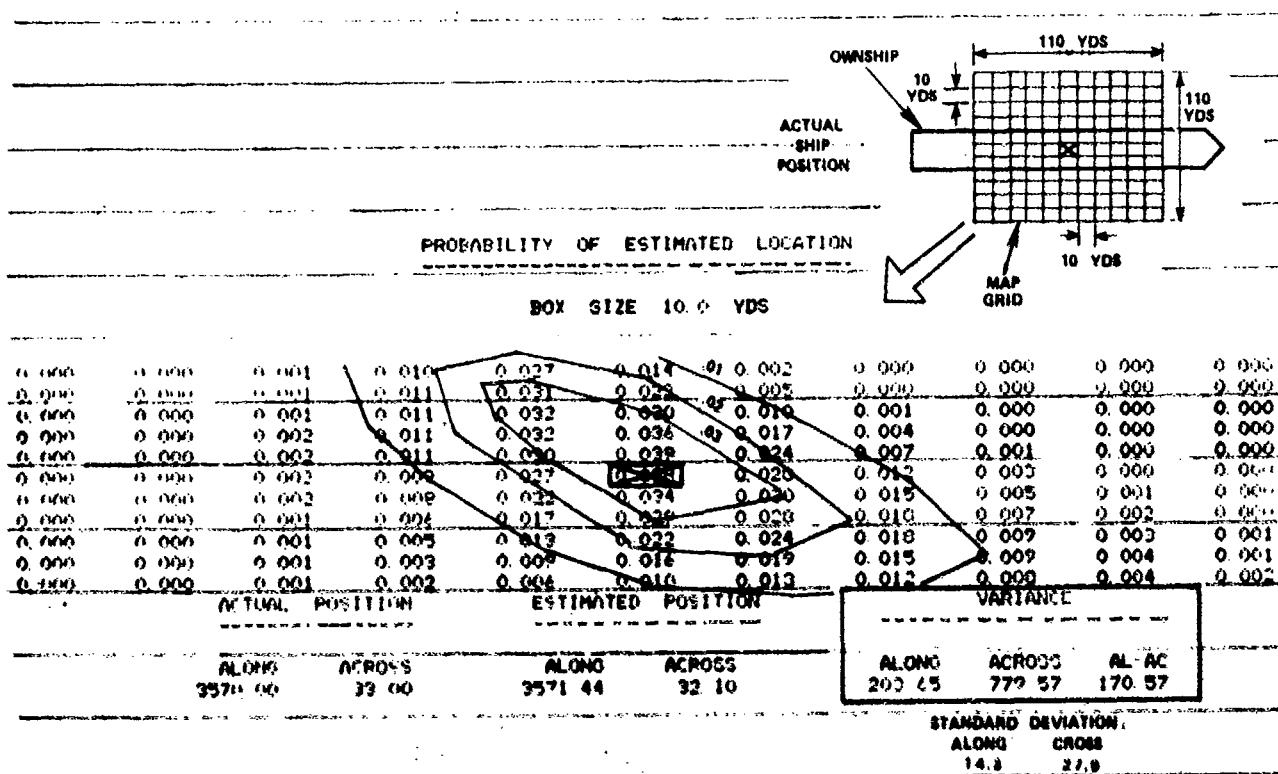


FIGURE 4-12. OUTPUT DATA SHEET FOR FIX MODEL A



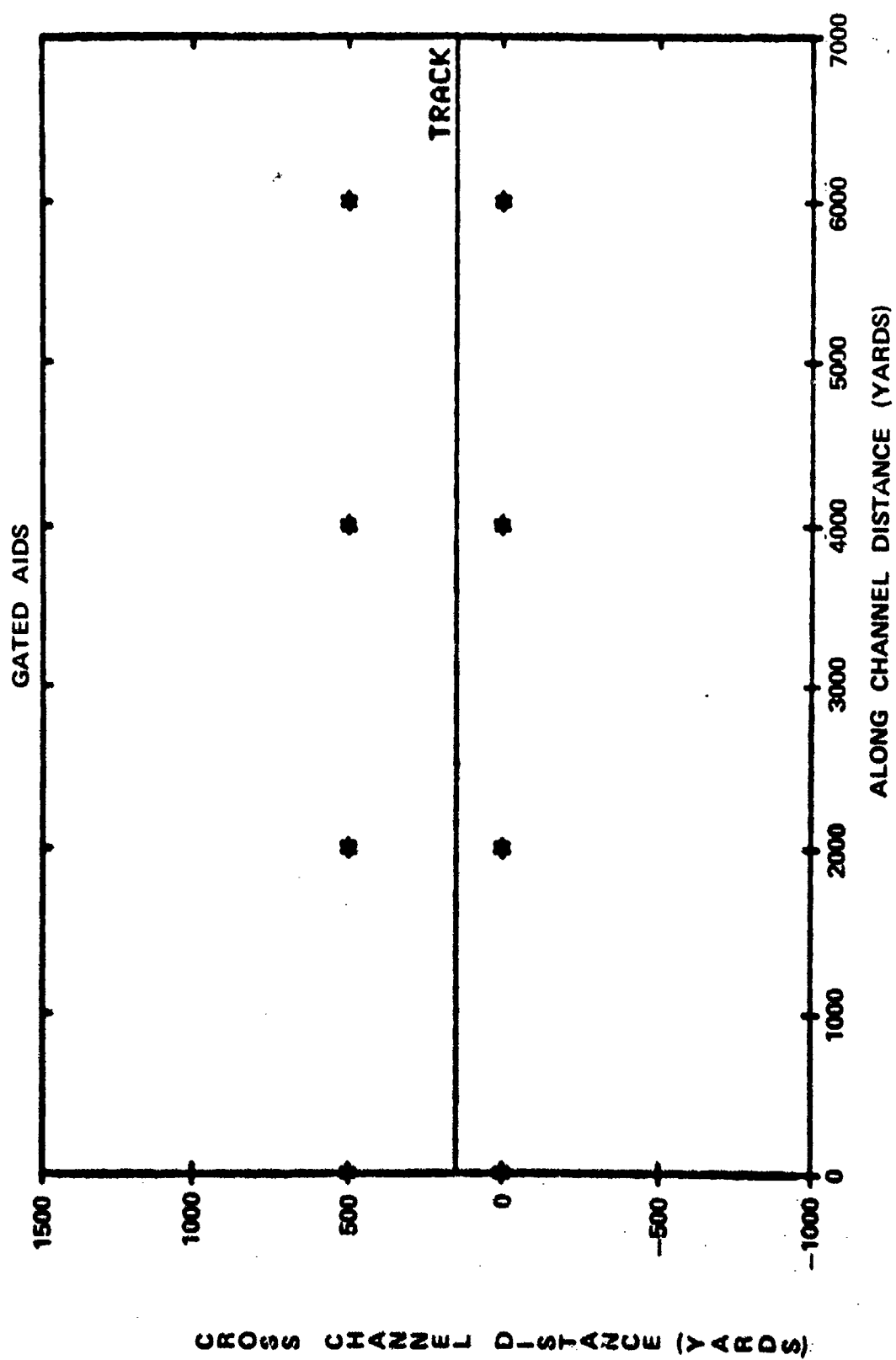


FIGURE 4-13. CROSS TRACK POSITION RELATIVE TO EIGHT AN'S

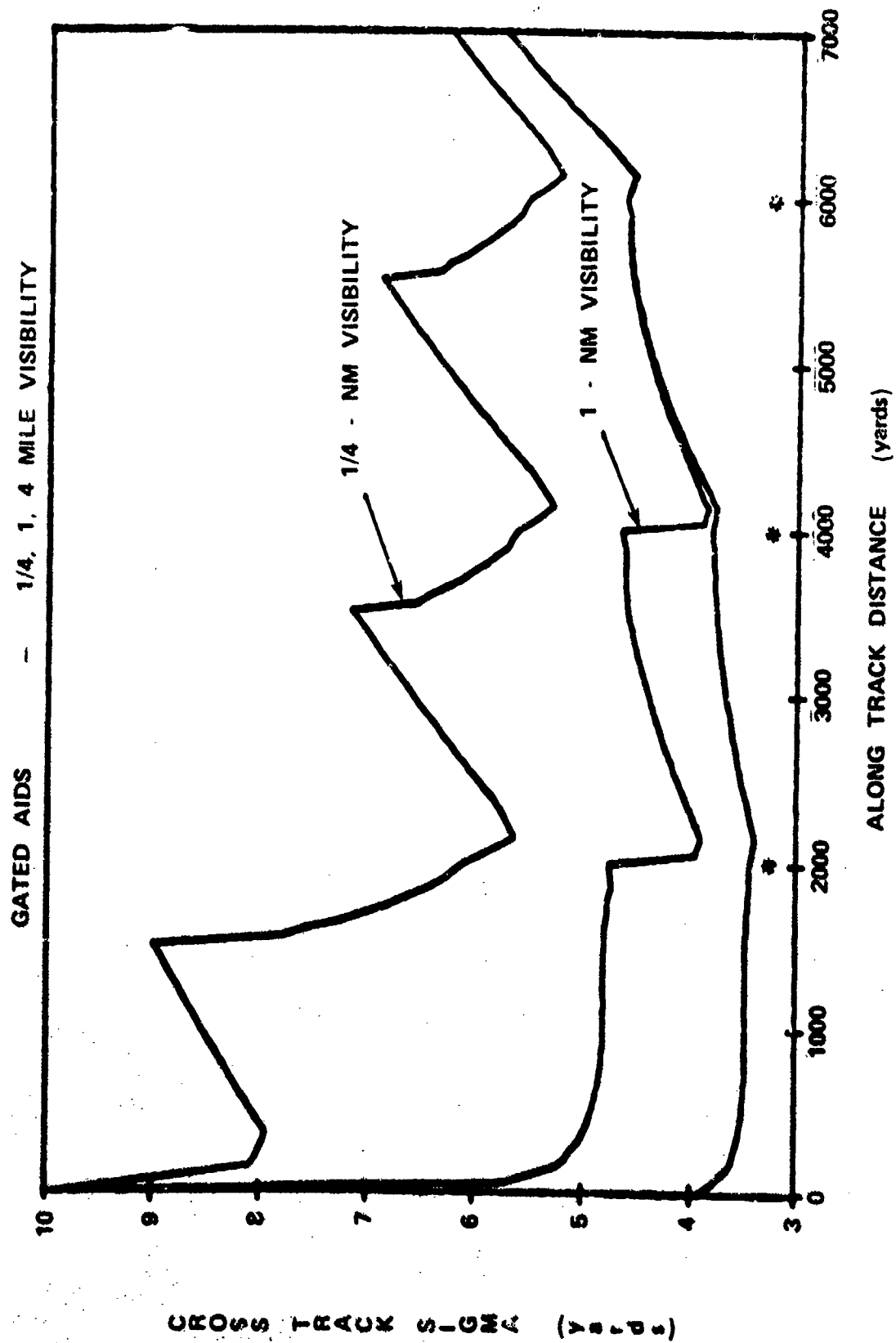


FIGURE 4-14. CROSS TRACK STANDARD DEVIATION FOR FIX ACCURACIES CALCULATED ALONG THE TRACK

Several buoy spacings and patterns (e.g., staggered versus gated) were evaluated in minutes using this approach. This anticipated use may be of value at the district office level where large computing facilities are less convenient. Further exercise of the fix model will ultimately establish its use and proper interpretation of the output measure of effectiveness.

#### 4.4.2 Navigating and Steering Model

The navigating and steering model simulates the entire navigation process and outputs measures of effectiveness as to how accurately the vessel is navigated and steered along a defined track. The model structure is comprehensive in that it allows the study of placement of fixed and floating aids, accuracy requirements for RAs, required detection ranges, AN reliability, and the alternate effects of using lateral or cardinal systems. The model structure allows navigation behavior, AN use, and ship response to be simulated in coastwise and piloting waters, port approaches, harbors, channels, and rivers. The hydrodynamic part of the model allows evaluation of a range of vessels from recreational craft to VLCCs (500,000 dwt). Finally the model output data, as generated by the currently developed portions of the model, compare well to at-sea and ship simulator data on a one-for-one basis at various points in the navigating and steering process (e.g., detection, fix, helmsman behavior).

Seven general subroutines in the navigating and steering model are:

- AN detection and perception
- Fix estimation
- Navigator's decisions
- Navigator's actions
- Helmsman steering process
- Dead reckoning process
- Ship's hydrodynamic response.

Given proper input coefficients and input logic, each subroutine can be made to simulate the behaviors required for simulating various ANs, their use in diverse geographic areas, and different vessel sizes. Output data are available from all subroutines; however, the principal model output is the navigational accuracy measure of effectiveness. This measure derives from the resultant ship's path over the defined track or channel.

The general structure of the model is shown in FIGURE 4-15. When ANs are selected, a fix is estimated. Decisions based on the fix result in actions. The helmsman complies with any orders; the ship responds. The process is repeated.

The variable time step block in the model controls the various processes to allow detection, fix, decisions, and actions to occur over several minutes while the helmsman and ownship's dynamics update every 3 seconds. The bold feedback lines originating from the action block indicate that the logic in this block can control and modify the operation of most other blocks. For example, an action statement can ask to have a fix taken only when a specific AN is abeam and every 60 minutes thereafter; or action statements can order the helmsman to change course when the decision is made that a turnpoint has been reached. The program control exercised by unique combinations of decisions and action statements (i.e., logic) provides the basic flexibility of the model for modeling navigation.

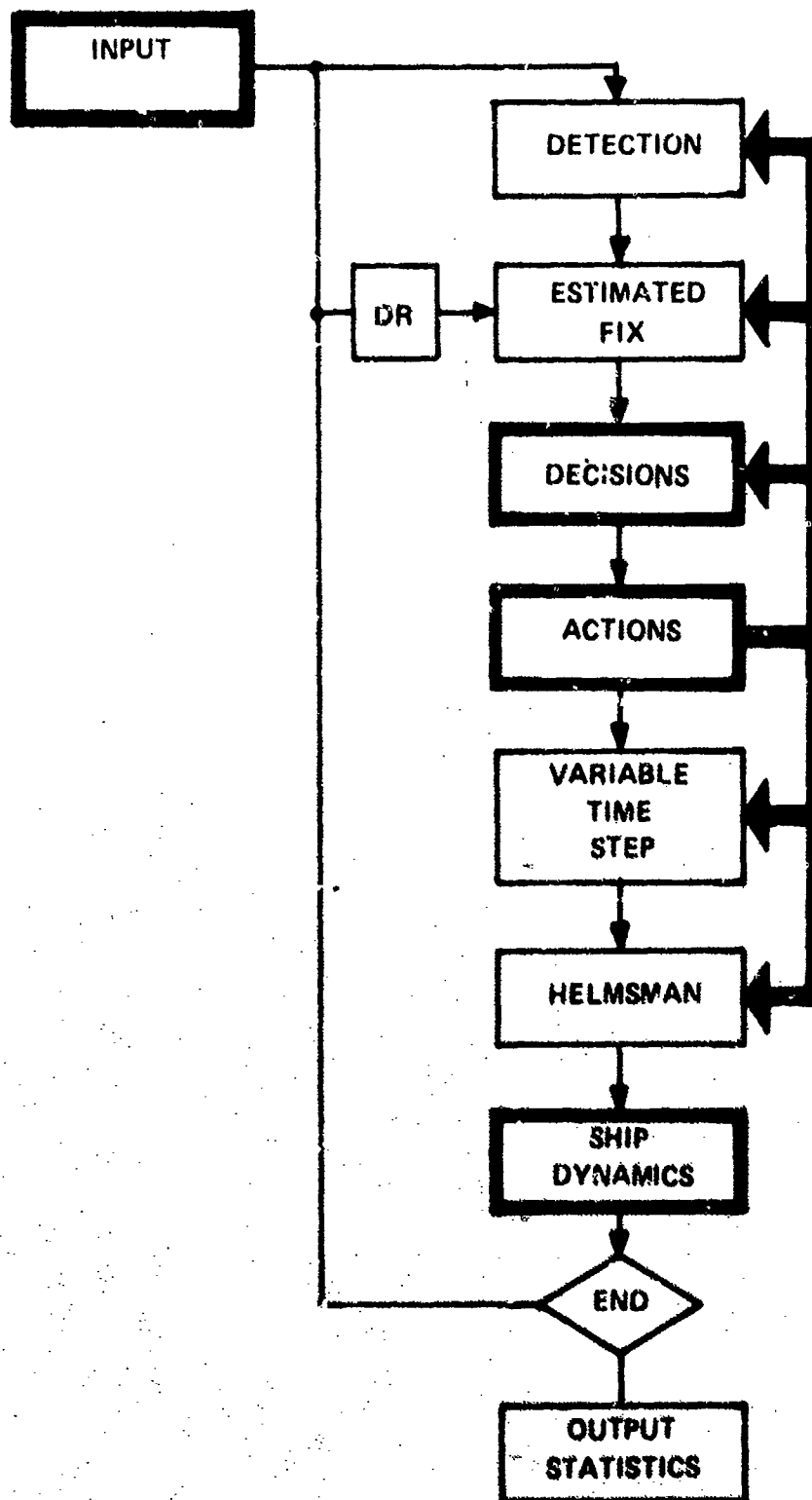


FIGURE 4-13. DISTRIBUTIONS IN MANEUVERING MODEL.

in many areas with diverse ANs. The diagram in FIGURE 4-16 shows that action and decision statements are inputted to the master program for each type of scenario run. Thus, the navigator's behavior could be customized for each specific set of ANs and RAs and each vessel type under consideration. The intermediate block "syntax translator" allows the model user to define decision and action statements in English language context. These statements are then automatically translated into the required logic codes required by the model.

Model subroutines indicated in FIGURE 4-15 contain all equipment, perception, and behavior error distributions discussed in Section 4. Basic operation of the model is as follows:

a. Detection. ANs are detected according to radar, daytime, night, or limited visibility mean thresholds and detection distributions. Each aid is either detected or not detected. Ranges and bearing to aids detected are estimated by random selection from radar error and visual perception error distributions. Action statements control detection frequency and the decision to use radar or visual techniques.

b. Fix Estimation. Visual perception ranges and bearings are correlated as a function of relative ranges, bearings, and the observer's height of eye. Estimated position is determined by choosing the maximum probable position or minimum risk position of the combination of all "observed" visual bearing and ranges, radar bearings and ranges, RDF bearings, LORAN positions, and DR position. This subroutine is the dynamic piloting fix model discussed in the previous section. Action statements control the information to be used in the fix and the fix frequency. The fix can be determined from bearing information alone, range information alone, radar data only, pelorus bearing and radar range, etc. However, DR position is entered in every fix. Action statements can also increase or decrease the pilot's "confidence" in a particular source of information (e.g., RDF) by artificially changing confidence level.

c. Decisions. Decision statements can test a number of ship and AN conditions against preselected criteria and then direct the program to specific actions. Conditions available for test can be ship's estimated position and velocities, heading, confidence in fix, relative bearing to a specific AN, range to a specific AN, etc. Actions can be indicated when any one, a group, or a unique combination of decision criteria is met. Decision operations in the model are controlled by action statements to the extent that AN action instructions may define that only a particular series of decisions be tested. Variable response to cross track position is considered in this subroutine, randomly sampling from distributions describing the extremes at which corrective orders are initiated.

d. Actions. Action statements can direct the operation of detection, fix, decision, variable time step, and helmsman routine. Action statements can test ship's parameters (e.g., position, velocity) and "order" new headings, rpm, fix frequencies, detection equipments, etc. If ship progress is "decided" to be satisfactory, no action is taken. Action statements are the control criteria for both the navigating process and ship control.

e. Variable Time Step. This functional block in the model controls the timing of the various subroutines so that a number of processes can be simulated as occurring simultaneously. The block also provides the ability to change fix frequencies and control timed events. Typical timing routines controlled are ship dynamics (update every 3 seconds), helmsman control of rudder and testing for proper ship response (10 to 20 seconds variable interval), and fix frequency (3 seconds to 60 minutes variable interval).

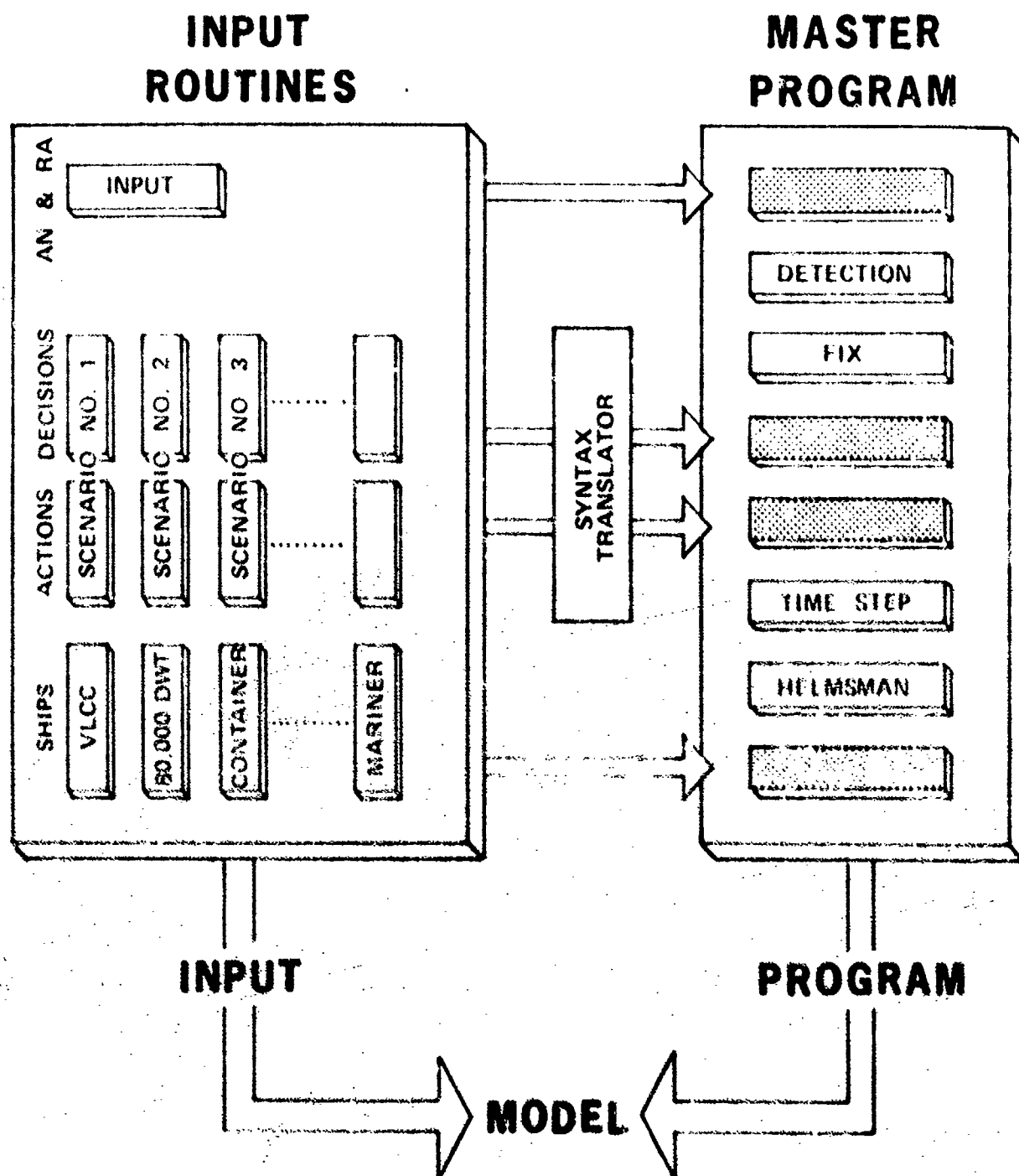


FIGURE 4-16. SYNTHESIS OF MULTIPLE SCENARIOS

f. Helmsman. The helmsman steers the ship in response to heading orders given by the action statement. This rather complex routine is designed to apply a rudder in the same manner as a helmsman at sea or a pilot giving rudder orders in both straight legs and turns (reference 23). Given an ordered course change, the helmsman selects an initial rudder angle to obtain the desired time to complete the turn and turn rate. This selection is obtained by simulating the mental actions of the helmsman (computer fast time) as he judges the ship's response to various rudders and then selects an optimum angle. The helmsman applies this rudder. If after a projected time, the turn rate is not as desired, more or less rudder is applied. Once the turn rate is achieved, the rudder is returned amidships, with the ship's momentum maintaining the turn rate. When the heading error becomes small enough, an optimum backing rudder is selected to stop the turn rate as course error reaches zero. Two areas of variable response are provided in this model; the first is the distribution of total time required to complete the maneuver; the second is roundoff error. Our model selects maneuver completion time, based on at-sea data, for each heading change. Applied rudder angles are rounded off to the nearest 5 degrees.

g. Ship Dynamics. Ship dynamics are represented in the computer model by a full set of hydrodynamic equations. These equations are identical to those used by MARAD at CAORF. Coefficients for many ships are available for these equations (Stevens Institute). Additionally, shallow water effects, bank suction, cushion, and wind and current are available for these equations if required. The inputs to these equations are rudder order (helm) and engine orders (rpm). Models of the steering engine and steam plant response produce appropriate thrust and turn moments for the ship model.

The output available from the various subroutines can be automatically plotted on a Calcomp plotter or printed out as listings on a line printer. Future development of these routines will allow automatic statistical testing for differences between AN configurations.

The simplest output format is a time-based plot of various parameters for a single transit of the vessel along the defined track. FIGURES 4-17 through 4-20 are typical time plots of one transit along a 3-mile channel, with gated buoys placed every 1-1/2 nautical miles. In this case, the pilot must determine the proper heading to compensate for a cross track current of unknown magnitude to establish a course made good along his intended track (90 degrees). To obtain the proper heading the decision-action statement modules representing the pilot behavior carry out the following strategy. The pilot makes a series of cross track position fix estimations as the ship travels along the channel. Each cross track fix estimation is checked for proper cross track position relative to the desired position and checked for cross track position relative to the previous fix to determine the amount and direction of the ship's cross track velocity. The pilot then orders an appropriate heading to direct the ship toward the desired track and course. Errors in fix estimation, however, present exact determination of the proper heading.

For the pilot strategy represented, the cause of the cross track velocity is not important. The cause may be from factors external to the ship such as wind, current, bank effects, etc, or internal such as propeller forces or initial heading. The effects may also change gradually or suddenly. The pilot's strategy is to counteract his perception of the effect by monitoring and correcting the cross track position and velocity of the ship.

FIGURE 4-17 shows the ship's initial heading and the time response as the pilot attempts to obtain the heading that will compensate exactly for the current. These data are from the ship's dynamics subroutines. FIGURE 4-18 shows the heading orders, derived from action subroutines. FIGURE 4-19 shows rudder response output by the helmsman subroutine. FIGURE 4-20 shows the variance of the pilot's confidence in the fix output by

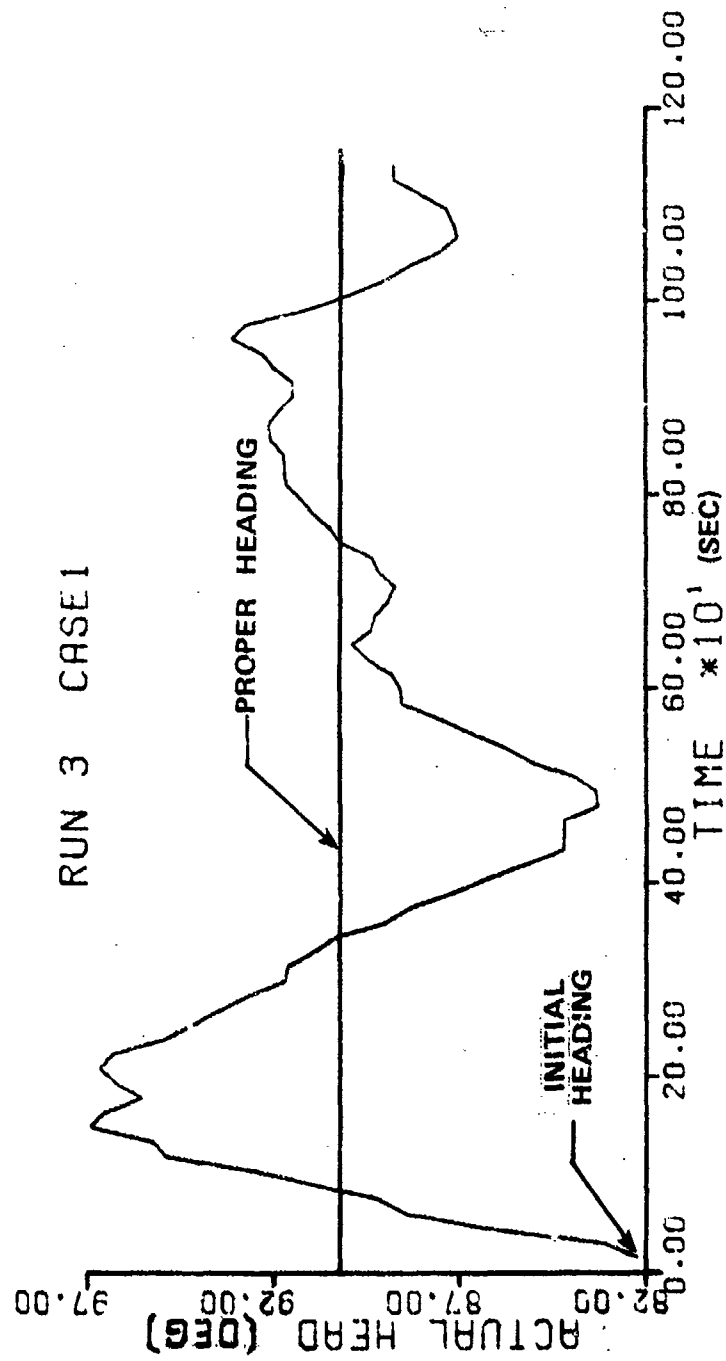


FIGURE 4-17. ACTUAL HEAD PLOT



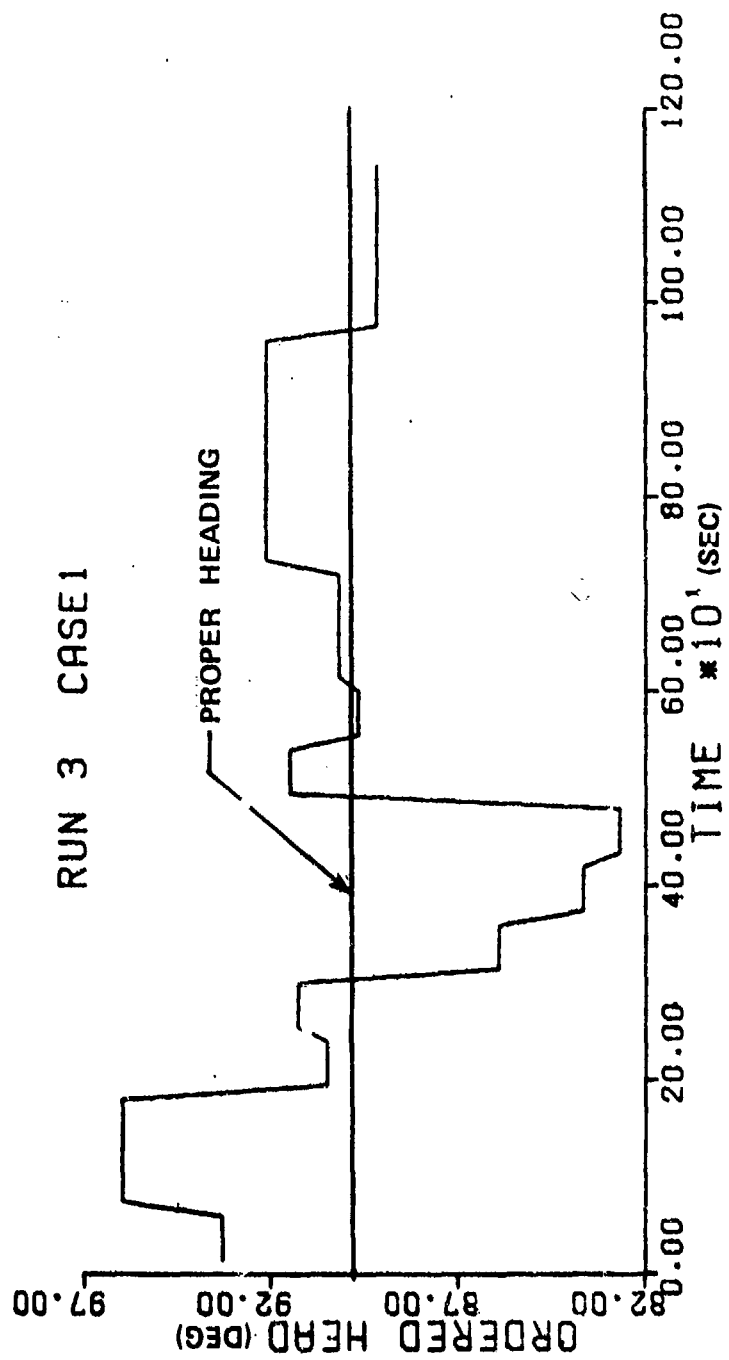


FIGURE 4-18. ORDERED HEAD PLOT

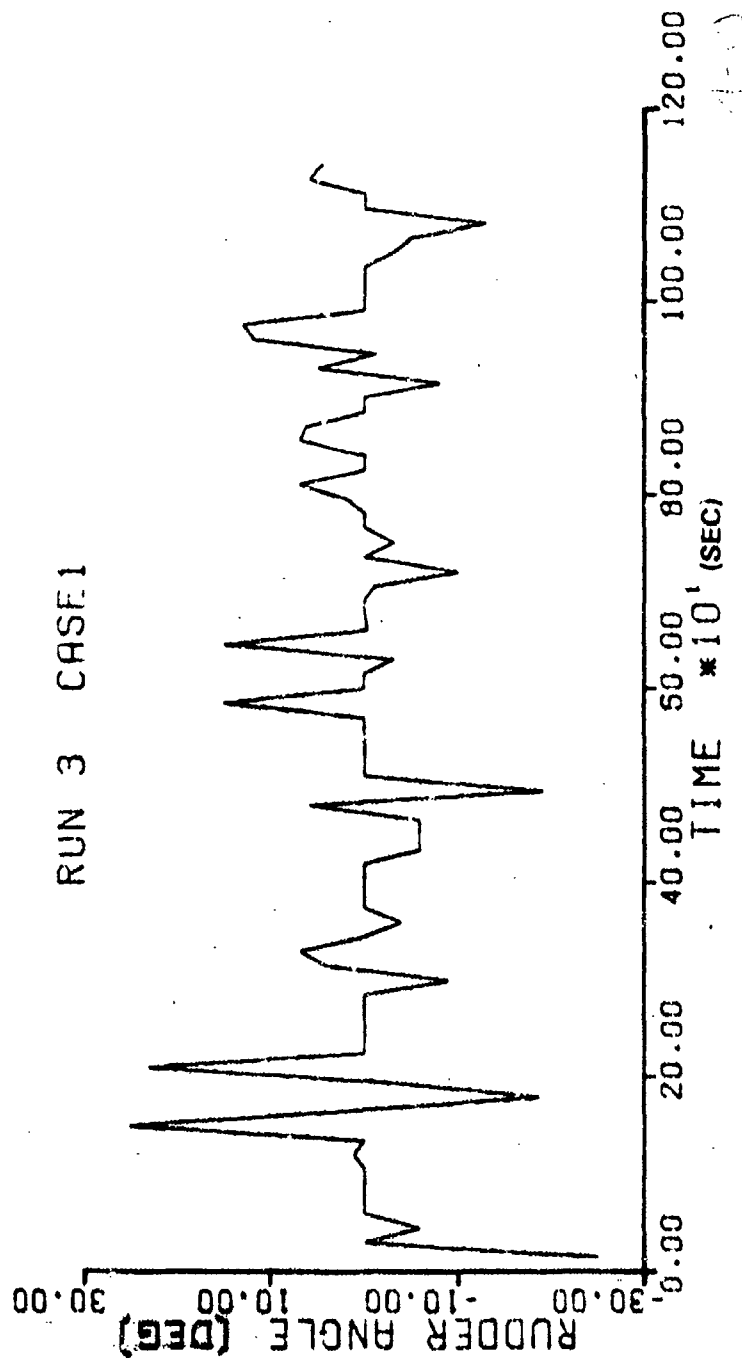


FIGURE 4-19. RUDDER ANGLE PLOT

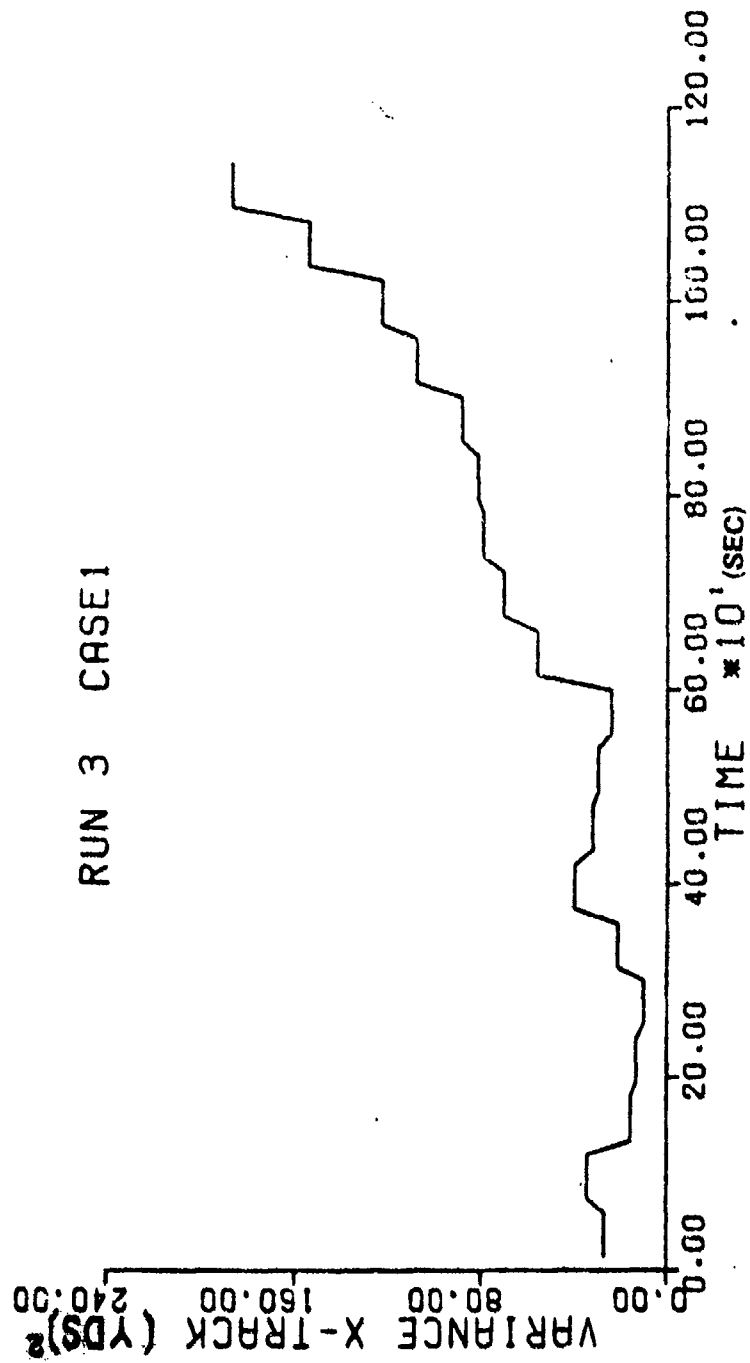


FIGURE 4-20. VARIANCE X-TRACK PLOT

the fix routines. This is the variance in the distribution of cross track positions described where the ship might also be, given the set of observations made by the pilot. Fixing in this case was totally by visual perception.

The time plots can be made on a macro scale of every 15 to 60 seconds for the plots indicated above, or on a micro scale of every 3 seconds for the study of particular responses. FIGURES 4-21 and 4-22 show the heading response generated by ordering a 20-degree heading change (92 to 112 degrees) and the helmsman's rudder orders. Two responses have been plotted to show the ability of the helmsman's subroutine to complete the maneuver at different time rates: 130 and 170 seconds. The rudder angle plots clearly indicate the helmsman's steering process: apply a rudder to start turn, order amidships, and apply a backing rudder as the ship settles on course.

This model can also output special map-like plots. FIGURE 4-23 shows four tracks of the ship's center of gravity along a 3-nautical mile channel, with gated buoys located every  $3/4$  of a nautical mile. Fixes were made using visual perception only. Again the pilot was required to seek a heading that would compensate for a cross current of unknown value.

The output data of the model may also be represented as statistical distributions and density functions, combining data from many simulated transits. This type format is the most appropriate method for presenting the measures of effectiveness of navigation accuracy. FIGURE 4-24 shows the cumulative swept width function of the channel for all the track plots in FIGURE 4-23. This curve was generated by summing in class intervals samples of the swept width recorded every 15 seconds, during all four runs, and then dividing by the total number of samples. The data values indicate the percent of time that an along track section of the channel is occupied by some portion of the hull. Cumulative probability data may also be plotted as output data. FIGURE 4-25 shows both the probability density function and the cumulative probability function for the cross track position of the ship's center of gravity (same runs as for FIGURE 4-24). The advantage of the cumulative probability plot is that it is easy to identify where the one and three standard deviations data fall as a function of probability values: 68 percent, 95 percent, and 99 percent. Additionally, given many runs, the small cumulative probabilities of a part of the ship lying outside the channel can be read off the plot. Probability density and distribution functions can be calculated and plotted for any of the variables in the model: fix variance, heading error, cross track velocity, turn rate, rudder angle, etc. Experience in studying at-sea and ship simulator data will ultimately indicate which variables beyond swept width may also provide good measures of effectiveness.

Application of the navigating and steering model to hypothetical problems, at-sea data, and in replication of CAORF data, indicates that the model has promise and that the feasibility of providing output measures of effectiveness which are sensitive to changes in AN configurations is quite acceptable. The demonstration and validation of this model are discussed in Section 5.

#### 4.4.3 Traffic Capacity Model

The traffic model is basically a model of a single channel. That is, it has arrival/departure points at each end of the channel through which traffic can arrive and depart. It can designate other arrival/departure points along either side of the channel which simulate side channels intersecting the modeled channel, or docks and anchorages where ships may stop. It can also locate traffic impediments at points along the channel which may be curves, regions of speed reduction due to wake restriction, narrow areas, or bridges. The representation of a channel within the model is shown in FIGURE 4-26.

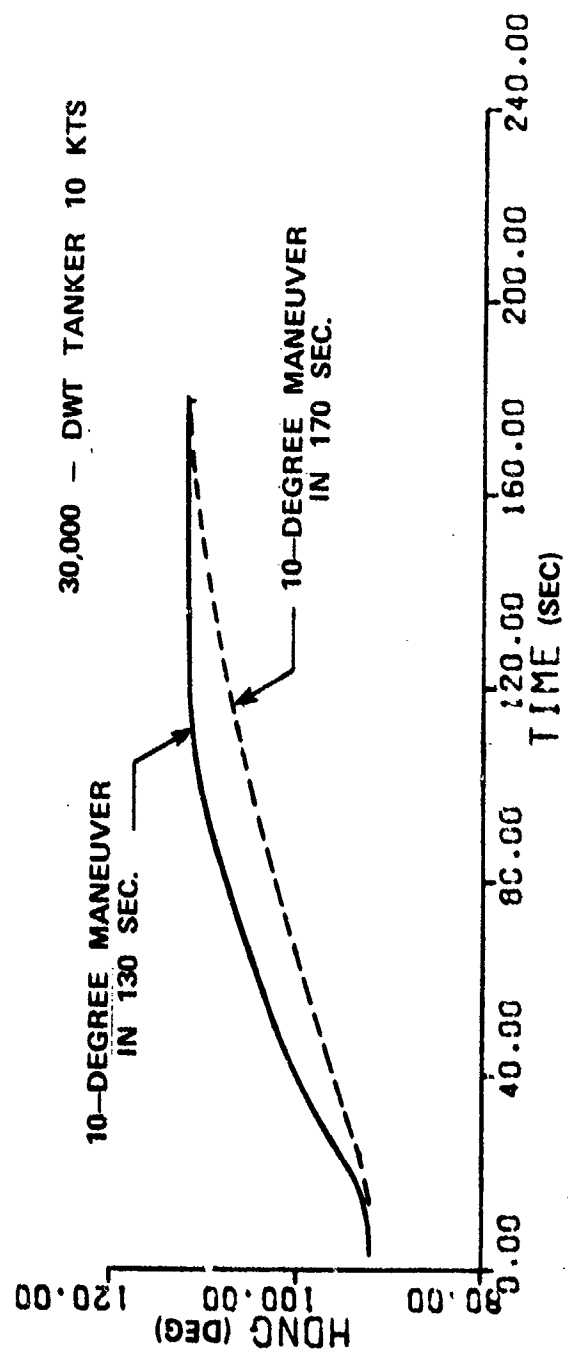


FIGURE 4-21. HEADING RESPONSE PLOT

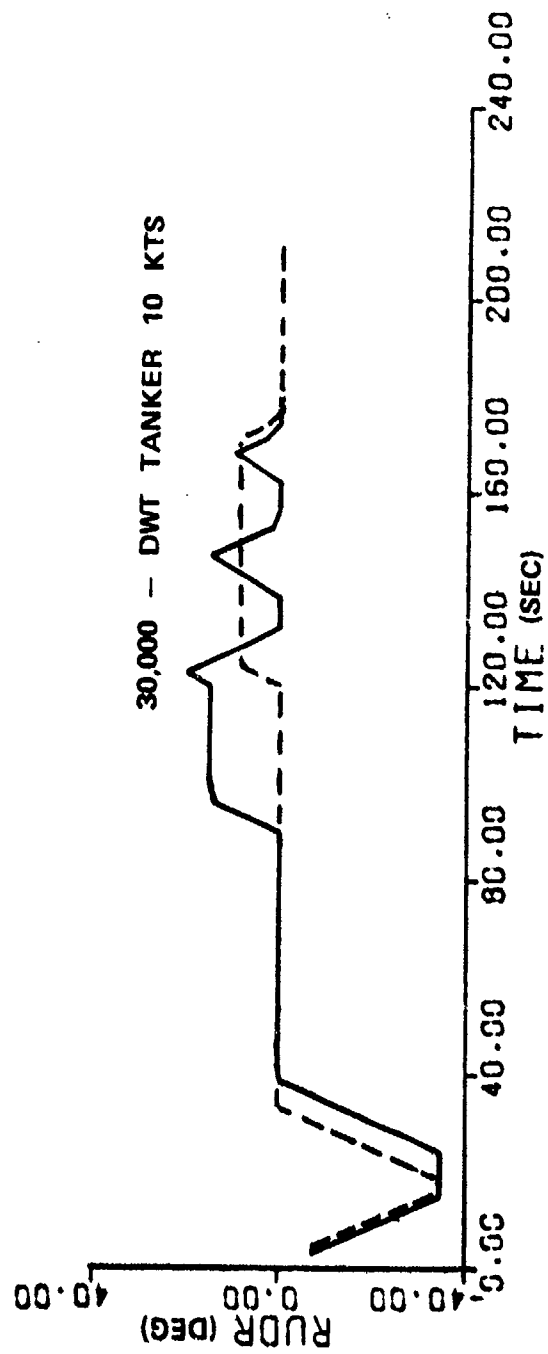
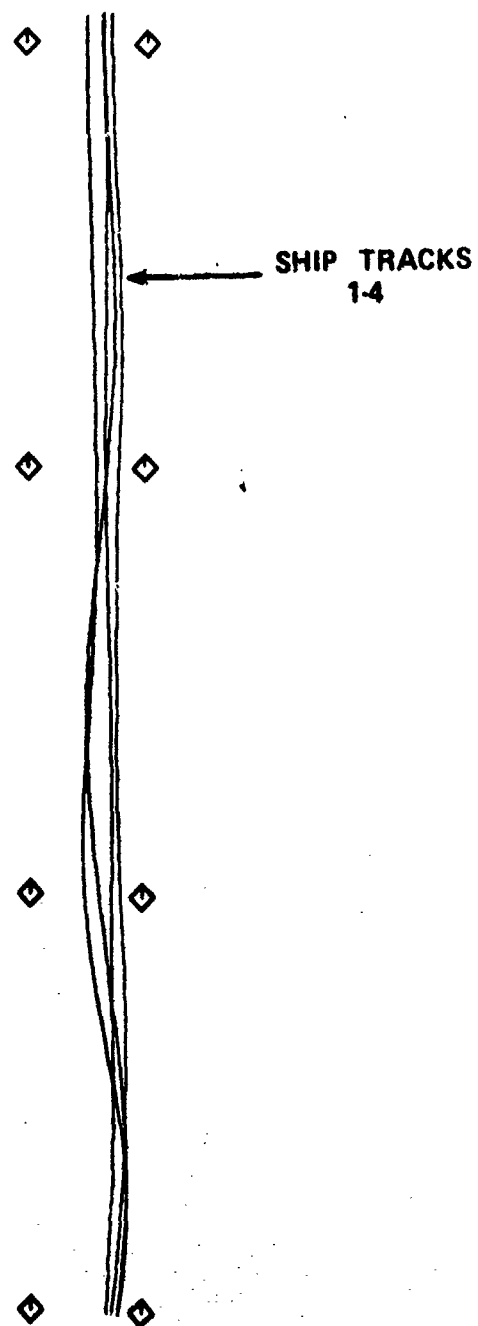


FIGURE 4-22. RUDDER RESPONSE PLOT



(533-YARD CHANNEL WIDTH, 3/4 NM BUOY SPACING)

FIGURE 4-23. SHIP CENTER OF GRAVITY PLOT

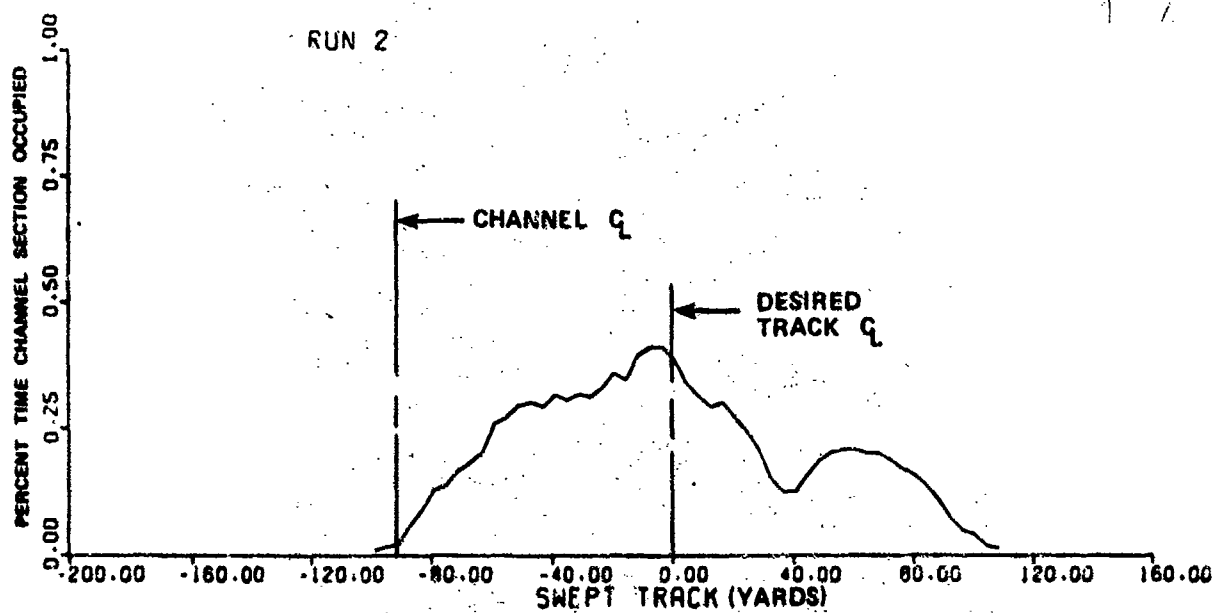


FIGURE 4-24. CUMULATIVE SWEEP WIDTH FUNCTION



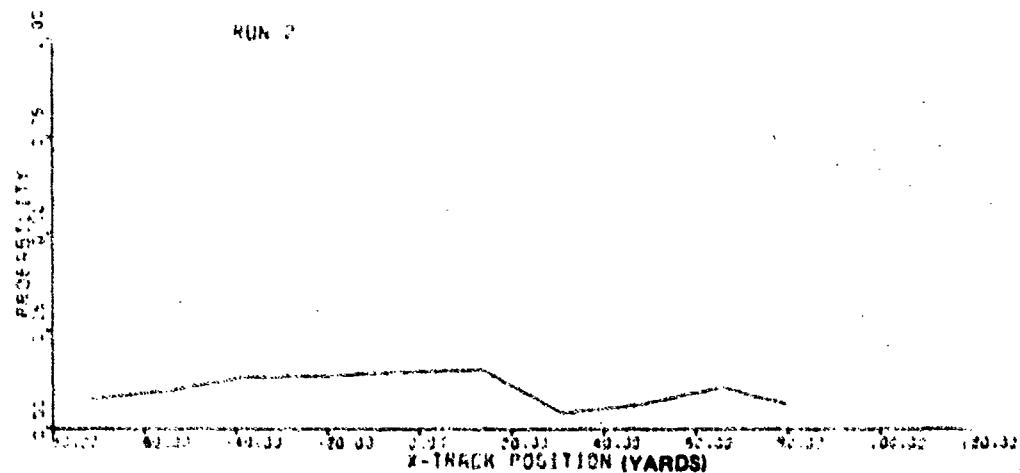
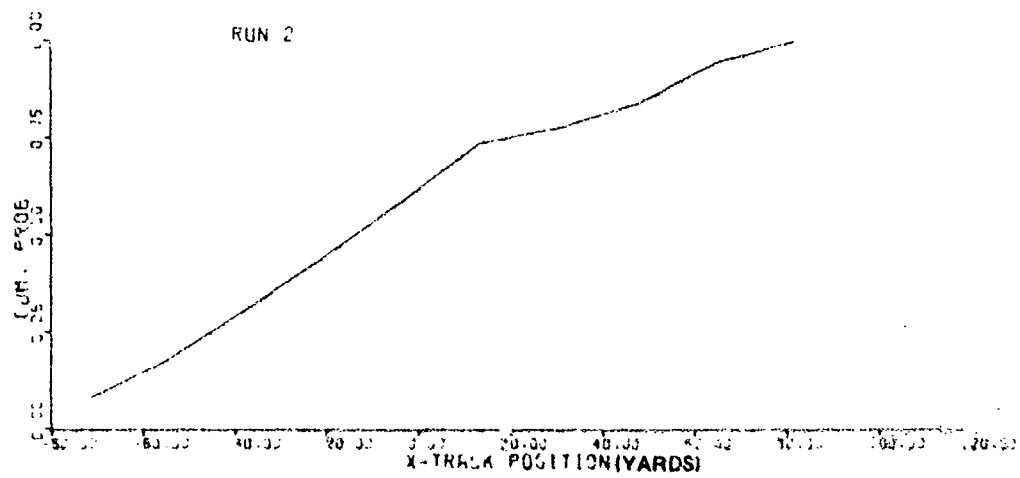


FIGURE 4-25. PROBABILITY DENSITY FUNCTION AND CUMULATIVE FUNCTION FOR CROSS TRACK POSITION

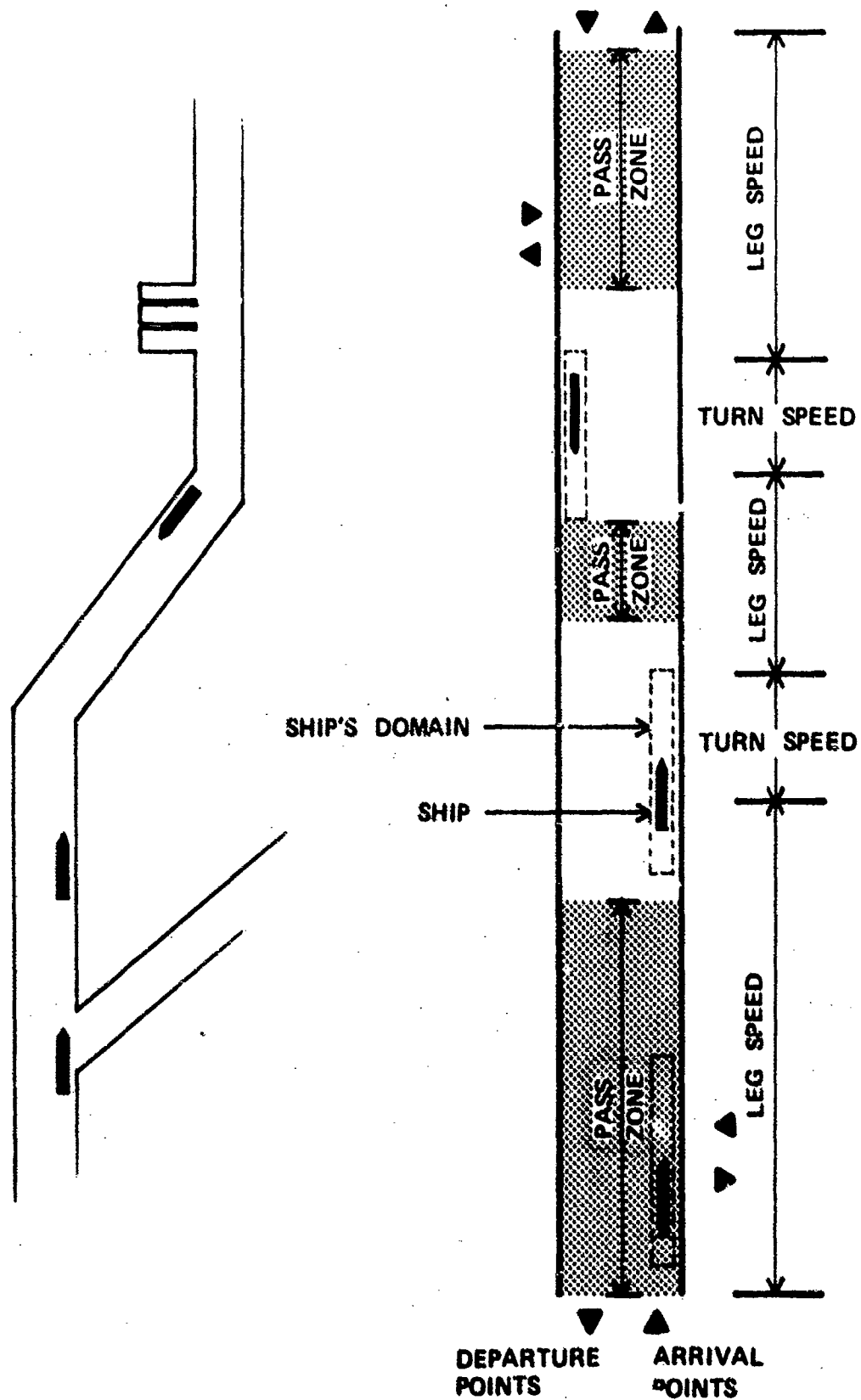


FIGURE 4-26. MODEL REPRESENTATION OF TRAFFIC FLOW

Many of the harbors of interest are basically single-channel harbors with feeder channels entering from the sides. The Delaware River to Philadelphia is a typical example. In more geographically complex harbors such as New York, the model may be used to study combinations of channels which form a particular route such as the route from Ambrose Channel through The Narrows, Kill Van Kull, and Newark Bay to the Port of Newark.

In the model, ships arrive at one of the arrival points at the ends or along the sides of the channel, travel along the channel to departure points, and leave the channel. In entering and traversing the channel, these ships are subject to the performance characteristics they possess and to the traffic policies established for the channel. These policies may be directly related to ANs, channel width, ship size, ship type, Rules of the Road, other traffic, and environmental conditions such as tide and visibility.

Ship arrivals are controlled by the model at each arrival point. The arrivals are timed by establishing a distribution of arrival times by ship type for each arrival point. These distributions have been assumed for this initial model to be Poisson with the mean arrival rate established by harbor authority or pilot origination records. The Poisson assumption was made to reflect independent random ship arrivals. Dependencies such as required tide conditions for channel transit are handled by channel use policies. These may require arrivals to be held at an arrival point in a queue until proper passage can be made. This includes ships waiting at channel entrances for flood tides, and ships which adjust their sea speed to arrive at the channel entrance at the desired time. The delay because of speed reduction is as real as if the ships were queued at the entrance.

Each ship is tagged with a ship type based on the percentage distribution of arrivals of ship types at that arrival point. Once the ship is typed, it is provided randomly chosen specific characteristics from percentage distributions of characteristics for that ship type in the harbor (e.g., speed, deadweight tonnage). It is then assigned a channel departure point. Departure points are selected by a random choice from the percentage distributions of departure points for ships of that type from that arrival point.

Ships traversing the channel after arriving at the arrival point and being assigned characteristics are subject to channel policies during their transit. These policies may include one- or two-way traffic on individual legs and turns, fore-and-aft separation guidelines for ships of certain types, clear channel distance necessary for ships entering from side arrival areas, and zones where overtaking is possible. As each ship traverses the channel, it must hold up, slow down, or stop according to decisions and actions based on its characteristics and the channel policies.

Through the fast time simulation capabilities of the computer, hundreds of channel transits representing many days or months of actual channel use may be studied. As each ship transits the channel, it will contribute to and be affected by the traffic. FIGURE 4-27 is a basic flow chart of the traffic model operation. Each ship is created as it enters an arrival point, makes a series of decision/actions to traverse the channel, adding its data to the statistical base, and then disappears through its design at departure point.

To determine the effect on the ship, certain data are collected and "tagged" to the ship as it transits. These data are then combined first with that of other ships of the same type making the same transit (specific arrival to specific departure points) and second with all other ships making that transit. Data which are tagged to the ship include total delay time, ratio of speed made good to desired speed, percent time at reduced speed, and average transit time.

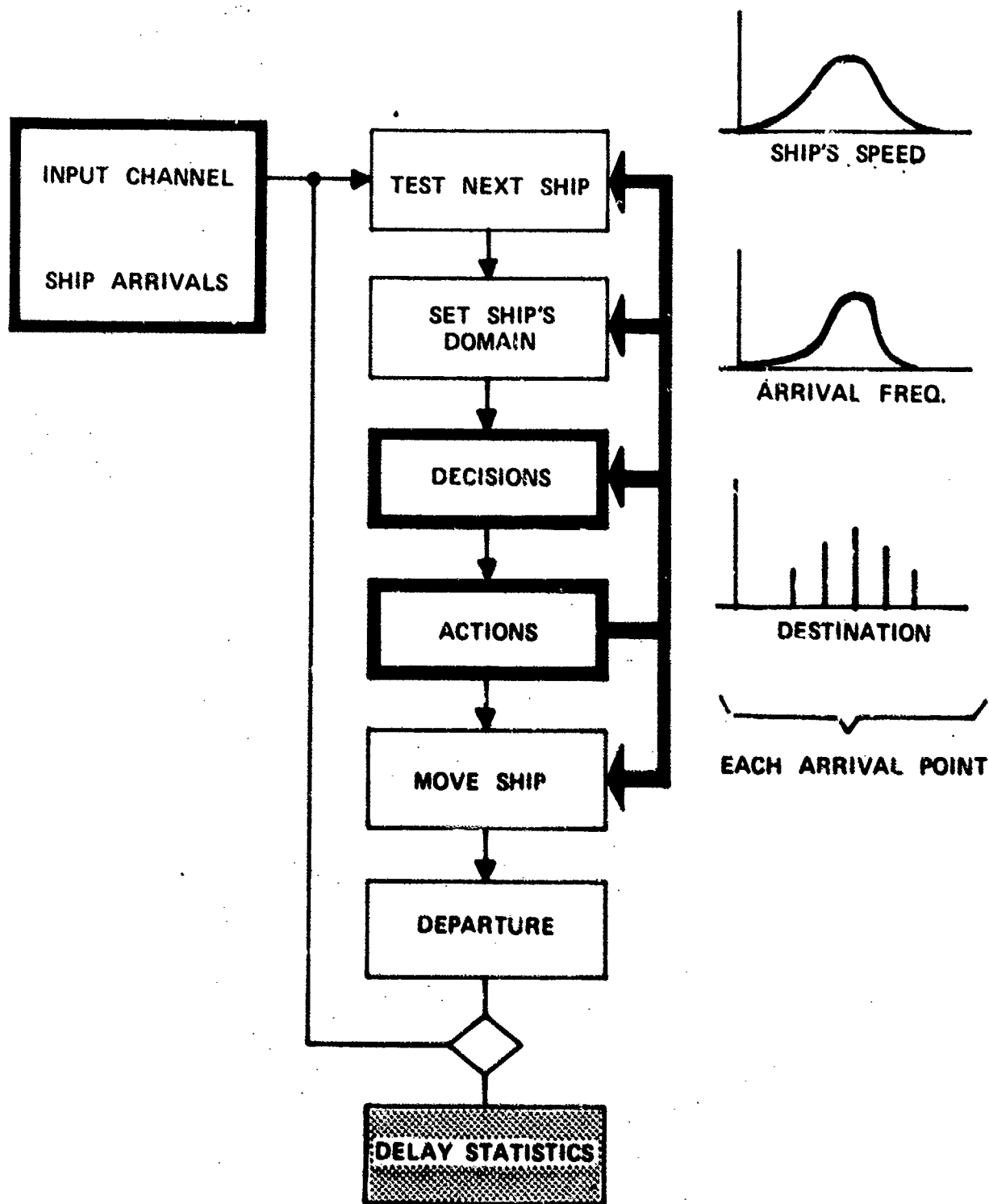


FIGURE 4-27. TRAFFIC CAPACITY MODEL - MONTE CARLO

Additional data were collected which reflect the traffic capacity of the channel, such as queue length and delay times at curves, and at arrival points. Model results provide an evaluation of the channel efficiency in handling the required traffic. Changes in arrival rates at the various arrival points can be used to evaluate changing traffic patterns or increasing and decreasing traffic loads. Changes in ship speeds, ship size, and type and channel use policies may be evaluated with respect to channel efficiency and ship transits experienced. Specific examples of these evaluation studies would be to determine the effect on shipping of the elimination of other traffic during transit of an LNG ship, the effect of fewer but larger ships, the effect of a more precise navigating capability in low visibility, and the effects of improved ANs in allowing meeting situations in turns rather than one-way traffic only.

To demonstrate the operation of the model, a channel example was run which consists of straight legs and one turn. Two-way traffic was permitted in the straight legs. Traffic was limited to one way in the turn. Fast vessels were not allowed to overtake slower vessels. Ships were introduced at either end of the channel at an average arrival rate of 1.5 per hour. Vessel maneuvering speeds were selected randomly from a Poisson distribution. The minimum vessel speed was 6 knots, the maximum 14 knots.

Output data may be presented in several formats: live CRT display, computer listing, or data plots. During problem solution in fast time, a CRT display can be viewed which illustrates all the ships presently in the channel and their progress. This option allows subjective evaluation of the limiting portions of complex channels. FIGURE 4-28 illustrates the representation of the sample channel with several ships in the system. The cross lines midway along the channel indicate the location of the turn. One ship is presently in the turn proceeding to the left. Another ship at the left has "slowed" to await clearing of the turn.

Summary data is automatically listed at the completion of each run. Data for the sample run are illustrated in FIGURE 4-29. The list includes each ship's identification number, its assigned maneuvering speed, and the wait time encountered in the channel. Positive speed values indicate vessels entered from the left end of the channel. Negative speeds indicate ships entered from the right. Data values at the bottom of FIGURE 4-29 indicate the average waiting time per ship was 5.9 minutes. The average transit time was 79.2 minutes.

The third output format for the traffic is a plot of delay versus vessel speed. These data for the sample run are indicated in FIGURE 4-30. Review of these data indicate the faster vessels encountered higher delays than the slower vessels.

Application of the traffic model to AN evaluation is illustrated in Section 5. Conversion of these delay data to economic losses to ship operators may be calculated utilizing per diem ship costs listed in TABLE 3-1. Generally, cost of ship delays becomes significant only if average transit time is affected in the order of an hour or two, passing through the entire harbor sea buoy to berth. Increasing traffic operations in limited visibility through judicial provision of ANs and RAs may have the greatest effect on annual traffic delays. This effect would be measured by the traffic capacity model.

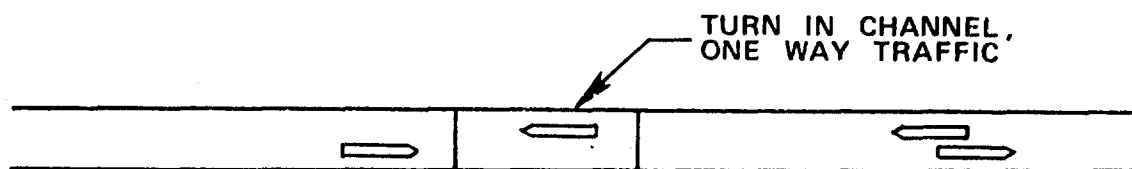


FIGURE 4-28. CRT DISPLAY OUTPUT FOR TRAFFIC MODEL

SHIP #	SPEED	WAIT	SHIP #	SPEED	WAIT	
1	7.3	10.0	26	13.2	11.0	
2	-8.1	0.0	27	-10.8	6.0	
3	8.0	0.0	28	8.1	0.0	
4	-8.0	0.0	29	12.5	14.0	
5	-7.4	0.0	30	-12.7	13.5	
6	9.2	10.5	31	-11.7	0.0	
7	-9.7	0.0	32	-13.5	0.0	
8	-6.6	0.0	33	-11.9	0.0	
9	11.7	0.0	34	-11.5	5.5	
10	6.1	9.5	35	10.4	0.0	
11	-9.0	0.0	36	-12.0	0.0	
12	-12.7	21.0	37	-11.0	6.5	
13	-9.8	0.0	38	-12.2	11.0	
14	-7.3	0.0	39	-8.4	7.5	
15	-12.7	0.0	40	-8.8	11.5	
16	-7.4	6.0	41	-8.0	0.0	
17	-12.8	4.0	42	-7.2	8.0	
18	-10.4	8.0	43	6.8	0.0	
19	-6.8	0.0	44	-6.8	8.5	
20	8.4	0.0	45	-12.3	8.0	
21	6.7	0.0	46	-8.4	4.5	
22	8.6	0.0	47	-11.4	2.5	
23	9.3	0.0	48	-9.1	8.0	
24	-9.8	0.0	49	13.1	2.5	
25	8.8	0.0	50	-7.1	0.0	
AVG. WAITING TIME =			5.9	AVG. TRANSIT TIME =		79.2
(MINUTES)				(MINUTES)		

FIGURE 4-29. LISTING OUTPUT FOR THE TRAFFIC MODEL



## Section 5

### DEMONSTRATION AND VALIDATION OF AID TO NAVIGATION PERFORMANCE MODELS

#### 5.1 INTRODUCTION

The ultimate success of the AN performance models will depend on:

- a. their sensitivity to AN configuration changes,
- b. their flexibility for use in studying ANs in various geographic locations, and
- c. their ability to match, and interpolate and extrapolate between and beyond, observed data.

During Phase I we attempted to show that the output measures of effectiveness are sensitive to changes in AN configurations. We also attempted to show that data output from the model matches the data values and trends observed in the at-sea and CAORF data bases to AN order of magnitude. We demonstrated the flexibility of modeling navigation in various geographic areas using different navigation techniques (radar versus visual) to take fixes at different intervals or on ANs of opportunity. We are confident we will be able to tune the models to optimum performance as more at-sea and simulator data become available.

#### 5.2 SENSITIVITY OF AN PERFORMANCE MODELS TO CHANGES IN AN CONFIGURATIONS

Several hypothetical but realistic problems were studied by the AN performance models. The purpose of these studies was to demonstrate that the major outputs of the models would vary as a function of changing AN configurations and navigating conditions.

##### 5.2.1 Sensitivity of Fix Accuracy Model

The expedient method of evaluating ANs is to apply the fix model to determine the standard deviation in fixes along predescribed track lines. FIGURE 5-1 shows two selected track lines along a sample channel 533 yards wide with gated buoys spaced every  $3/4$  of a nautical mile. Tracks are selected at mid-channel and quarter-channel because the majority of correction maneuvers are made along these lines.

The standard deviations (in yards) of the cross track visual fixes along each track line are shown in FIGURE 5-2. As expected, the standard deviation changes as a function of the buoy spacing, but surprisingly not as a function of the track-line position. The standard deviation grows slightly toward infinity at the end of the channel, because no buoys are in sight beyond and the program prevents the pilot from seeing aft. By comparison, FIGURE 5-3 shows similar track lines for a channel 533 yards wide but with a buoy spacing of  $1-1/2$  nautical miles. The standard deviation of the cross-track visual fix grows slightly as a function of increasing buoy spacing. (See FIGURE 5-4.)

Comparison of FIGURES 5-2 and 5-4 shows that, in clear visibility, fix accuracy is hardly affected by buoy spacing. However, this relationship is not true for limited



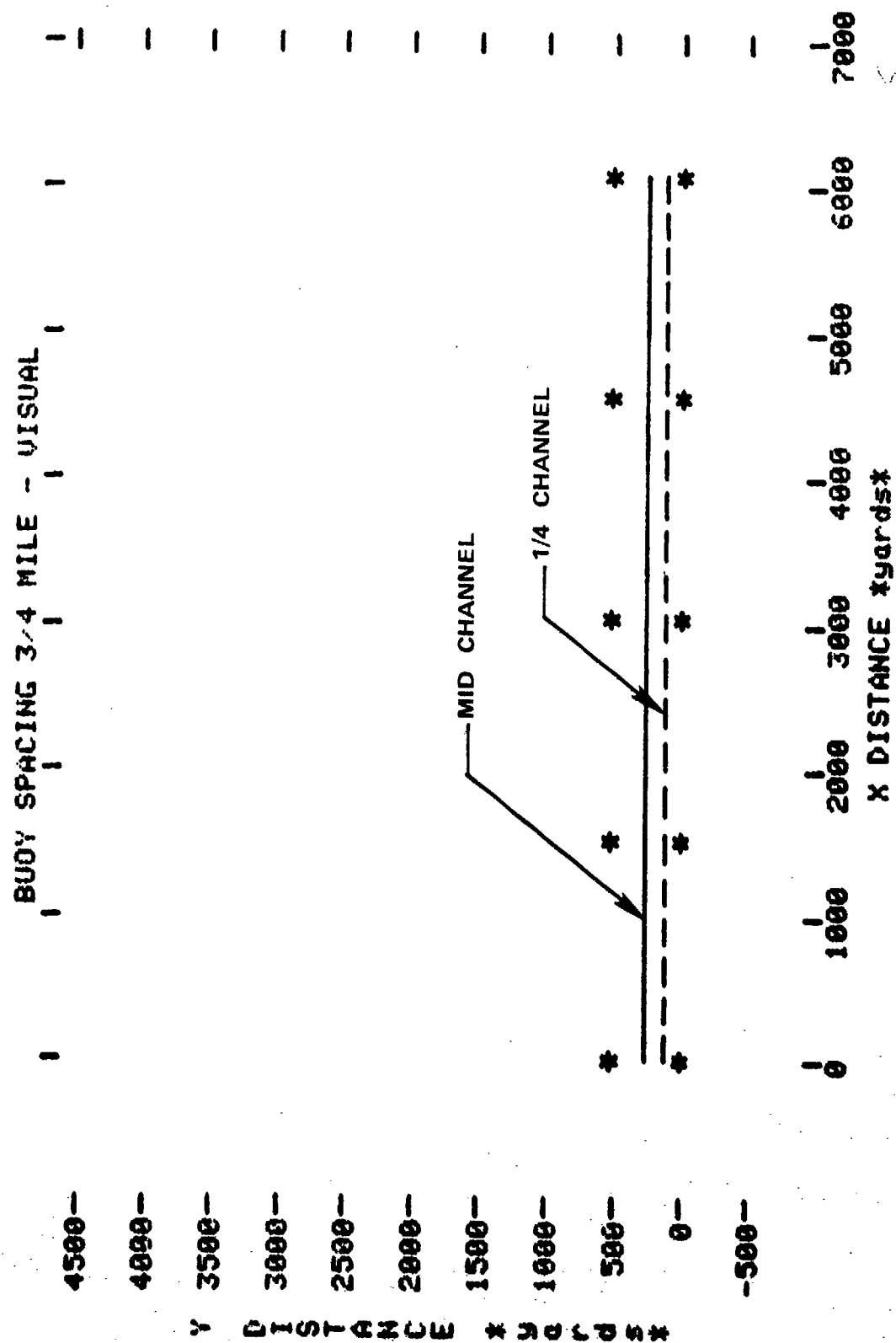


FIGURE 5-1. TRACKING FOR FIX INFORMATION, BUOY SPACING 3/4 NAUTICAL MILE

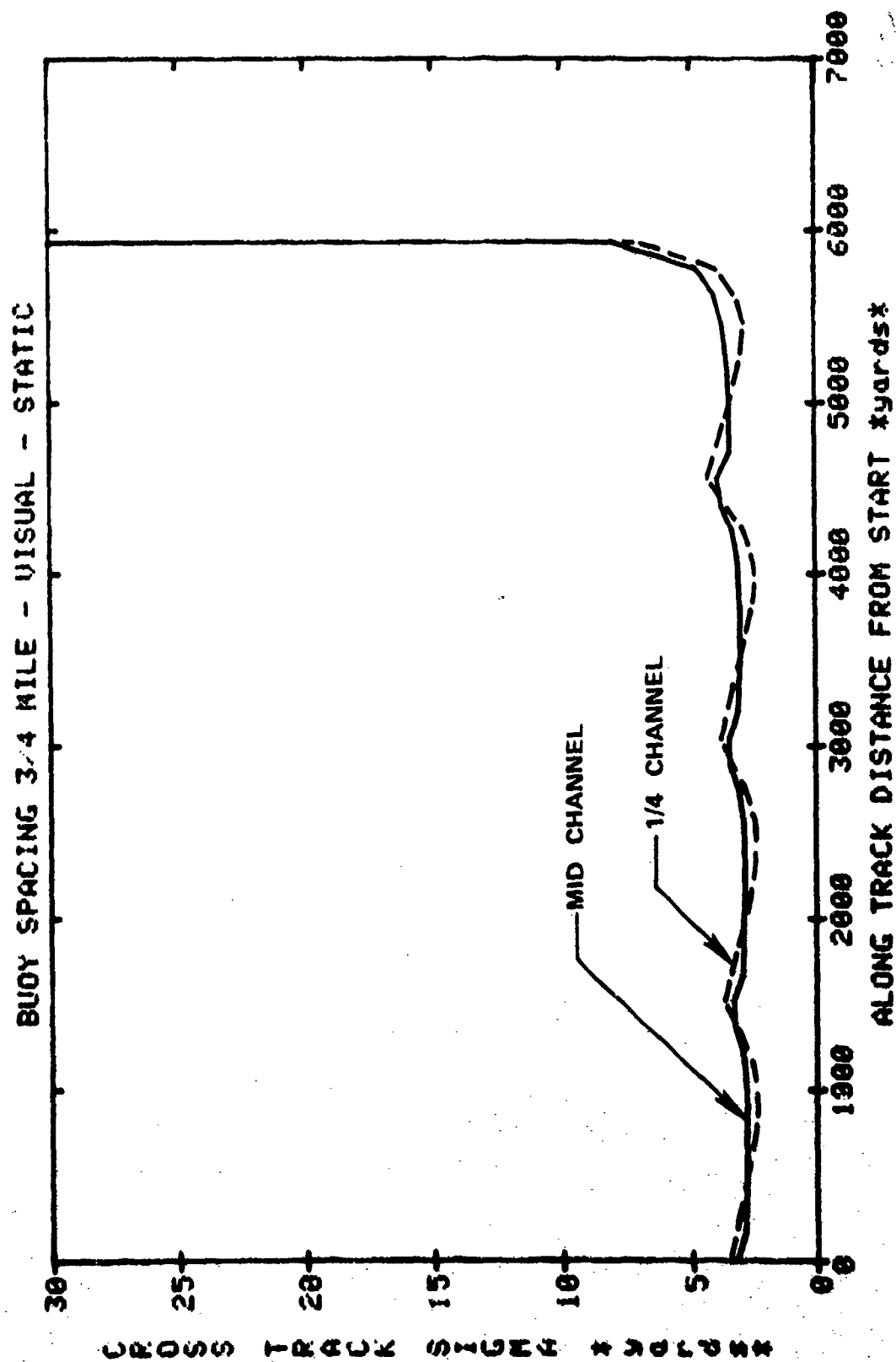


FIGURE 5-2. CROSS TRACK FIX STANDARD DEVIATION ALONG TRACK, BUOY SPACING  $3/4$  NAUTICAL MILE

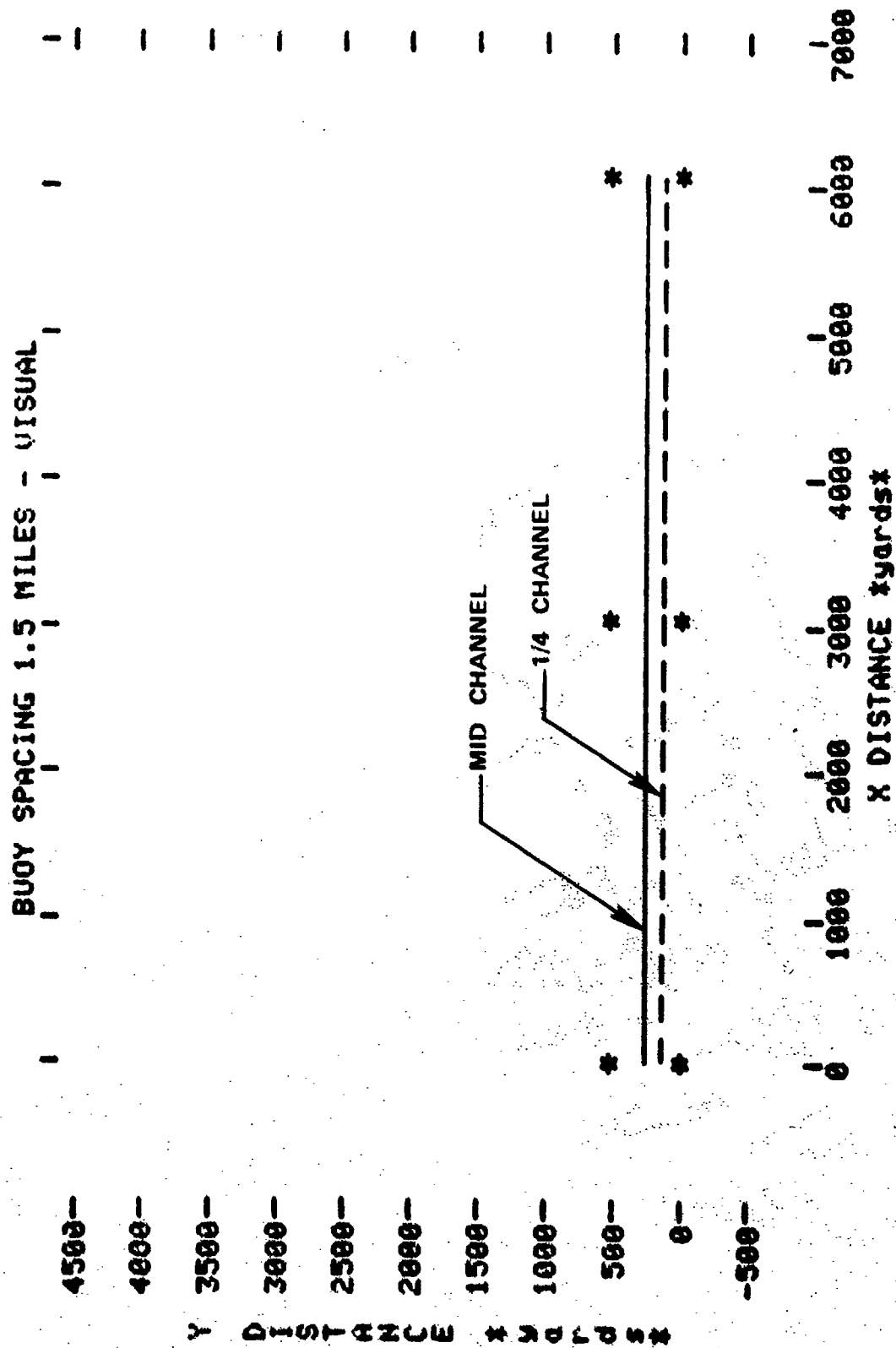


FIGURE 5-3. TRACKING FOR FIX INFORMATION, BUOY SPACING 1-1/2 NAUTICAL MILES

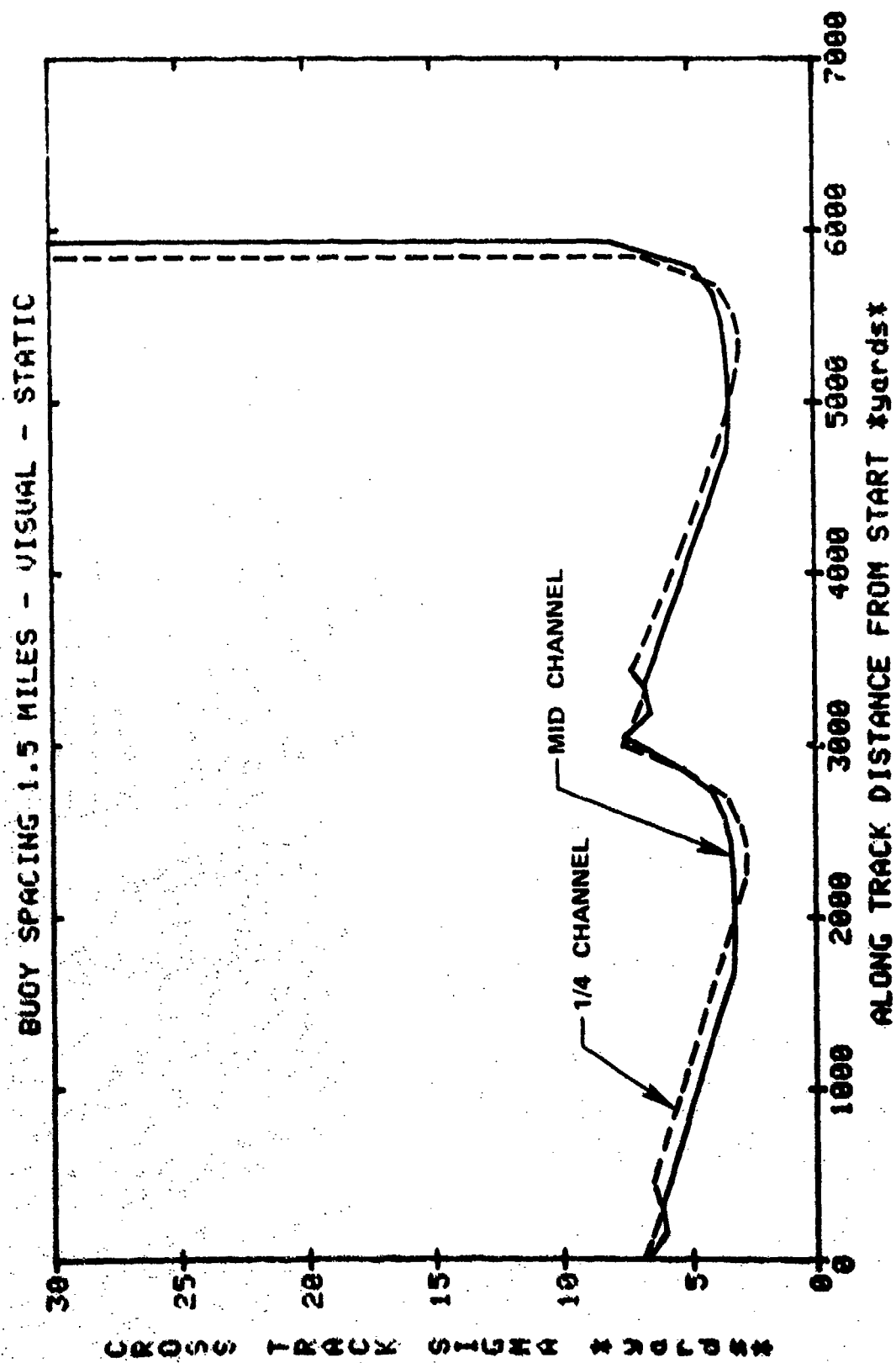


FIGURE 5-4. CROSS TRACK FIX STANDARD DEVIATION ALONG TRACK, BUOY SPACING 1-1/2 NAUTICAL MILES

visibility. The fix accuracy data run for the two AN configurations in 1/2-nautical mile visibility is shown in FIGURES 5-5 and 5-6. The spaces in these curves indicate regions where no buoys are visible ahead to allow estimating own ship's position. Data indicate the obvious: position information is less often available in limited visibility with increased buoy spacing; the accuracy of the usual fixes is identical in the two configurations, when the gated buoys are in sight.

The examples shown in FIGURES 5-1 through 5-6 were limited to the evaluation of visual fixes to floating aids. An exhaustive study of this particular channel would require evaluation of fix accuracy with radar and fix accuracies to fixed objectives. The relative safety of these channels will be determined by the navigating and steering model, which appropriately weighs the reliability of fixes taken on floating ANs against the reliability of fixes taken on fixed ANs. The navigating and steering model will determine how safely the ship is steered across the "blind" spots in limited visibility.

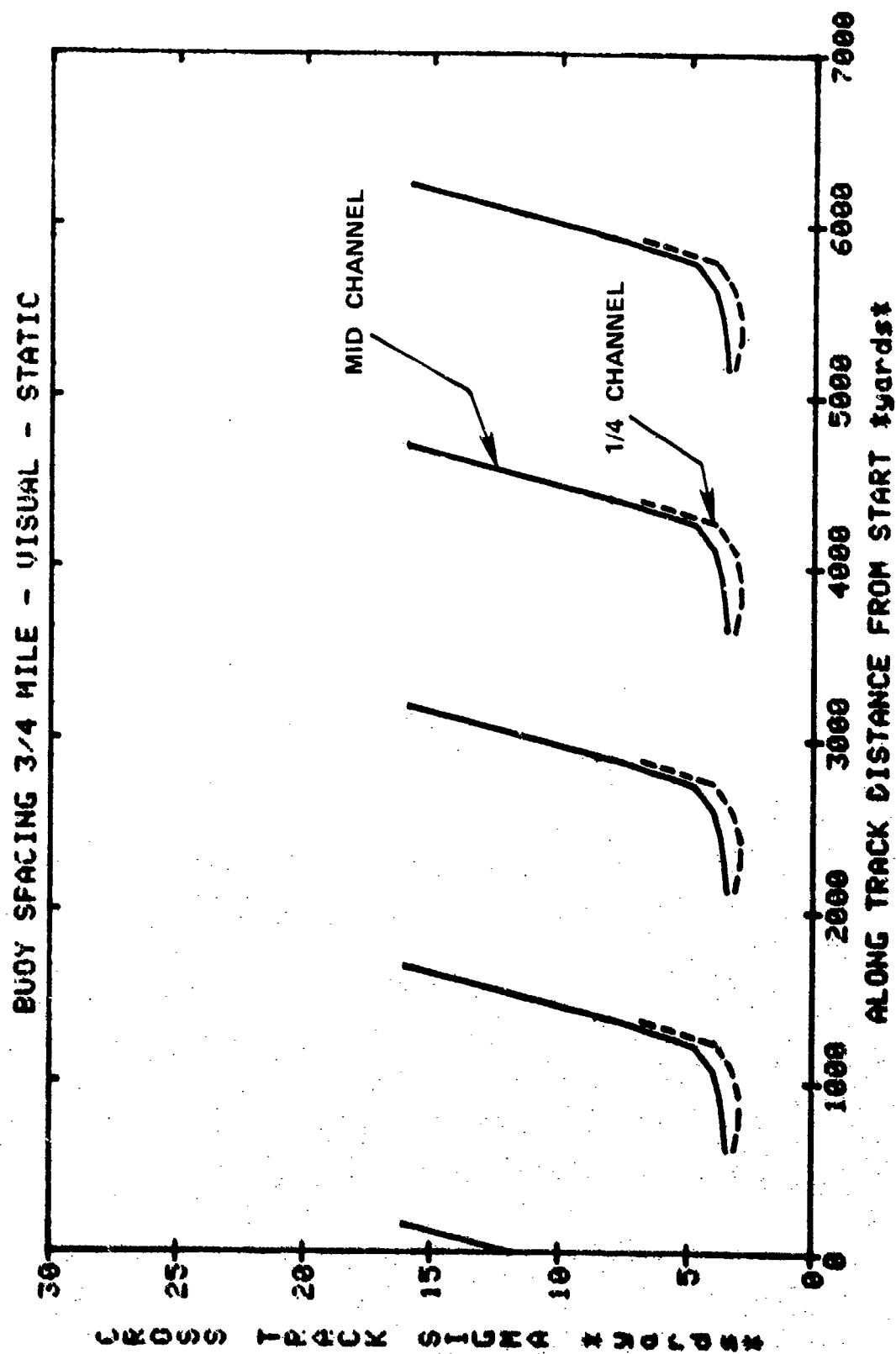
Data in FIGURES 5-2, 5-4, 5-5, and 5-6 illustrate that the output measures of fix accuracy are, in fact, sensitive to AN configurations. Evaluation of visual or electronic (e.g., radar) fix accuracies for any particular set of ANs or RAs provides a rapid method for trading off alternate AN and RA configurations. Only the navigating and steering model can determine the extent to which fix accuracy relates to safety for all vessels using the channels. The fix model alone is valuable in making macro tradeoffs between alternate AN configurations. When alternate AN or RA configurations provide identical fix accuracy, then cost or reliability variables can be applied to select the best configuration for continued evaluation in the navigating and steering model.

#### 5.2.2 Sensitivity of Navigating and Steering Model

The relative safety of a particular AN configuration can be determined by running the navigating and steering model for alternate AN configurations. FIGURE 5-7 illustrates track plots for four Monte Carlo case runs through the channels illustrated in FIGURES 5-1 and 5-3. Channel width is 533 yards; buoy spacing is 3/4 nautical mile and 1-1/2 nautical miles, respectively. The number of runs was limited to four for clarity of plotting. FIGURE 5-8 illustrates the resultant swept width plots accumulated over all Monte Carlo cases. These data indicate that the maximum swept widths were nearly identical for clear visibility. The visual fix accuracy data in FIGURES 5-2 and 5-4 show that there were no significant differences in accuracy to cause difference in the swept widths. However, under limited visibility, the relative safety might not be as high. This was tested by changing the visibility threshold in the model. FIGURE 5-9 illustrates track plots for the same channels with only 1/2-nautical mile visibility. The swept width curves in FIGURE 5-10 indicate that the ship wanders much farther cross track, given a buoy spacing of 1-1/2 nautical miles. In several cases, the ship leaves the channel on the starboard side with 1-1/2 nautical mile buoy spacing. Additionally, the ship inadvertently crosses the centerline into oncoming traffic lanes. The threat of grounding and collision in limited visibility thus appears to be higher for more widely spaced buoys.

The ultimate selection of 3/4-nautical mile or 1-1/2-nautical mile buoy spacing will depend on further investigation of navigating the channel:

- a. with multiple sensors (radar),
- b. at night, and
- c. under extreme wind and current conditions.



**FIGURE 5-5. 1/2-MILE VISIBILITY, BUOY SPACING 3/4 MILE**

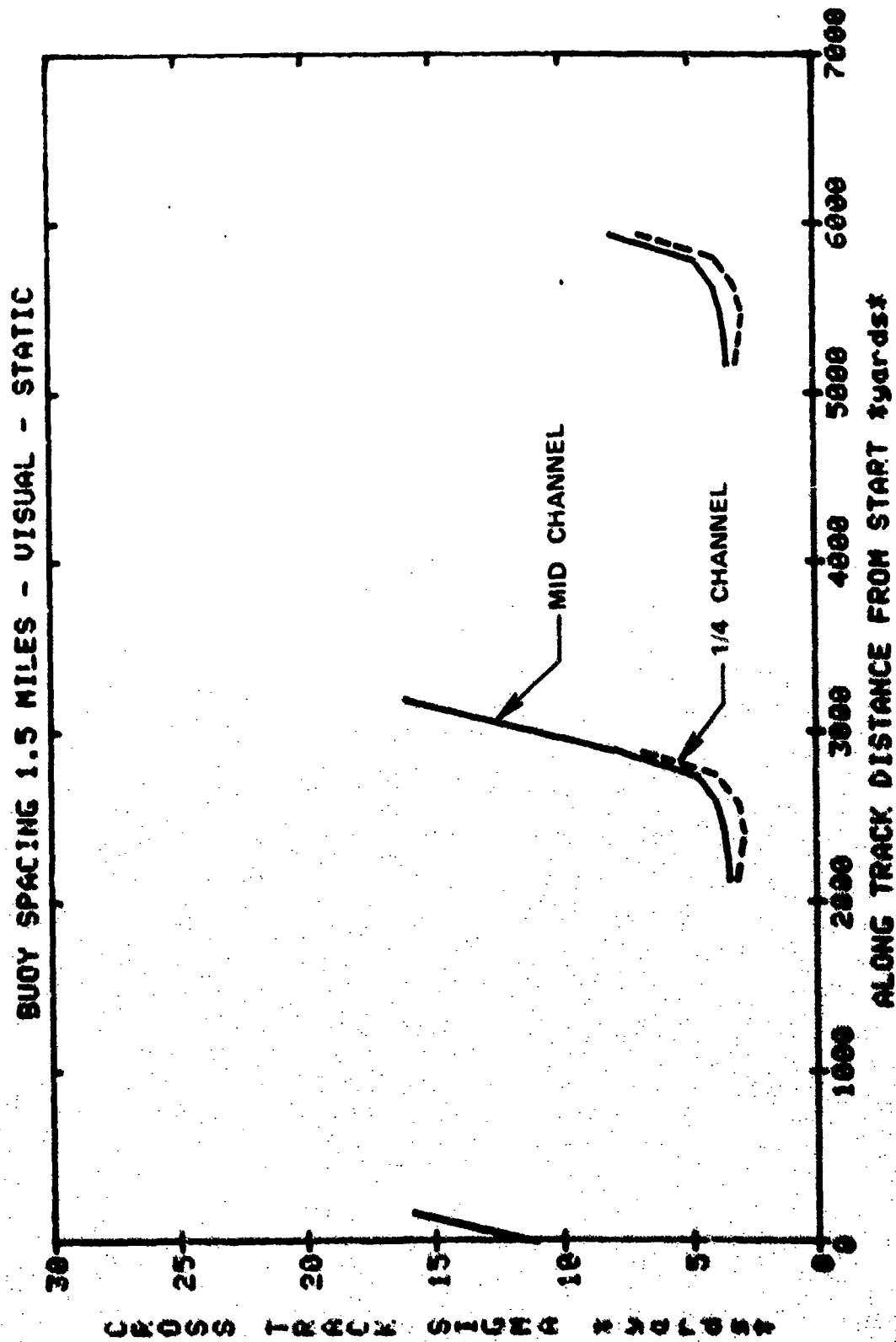


FIGURE 5-6. 1/2-MILE VISIBILITY, BUOY SPACING 1-1/2 MILES

DIRECTION OF TRAVEL →

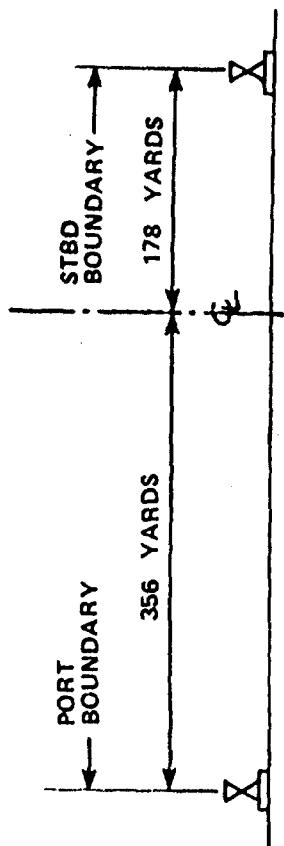
RUN 1  
(533-YARD CHANNEL WIDTH) 3/4 NM BUOY SPACING

DIRECTION OF TRAVEL →

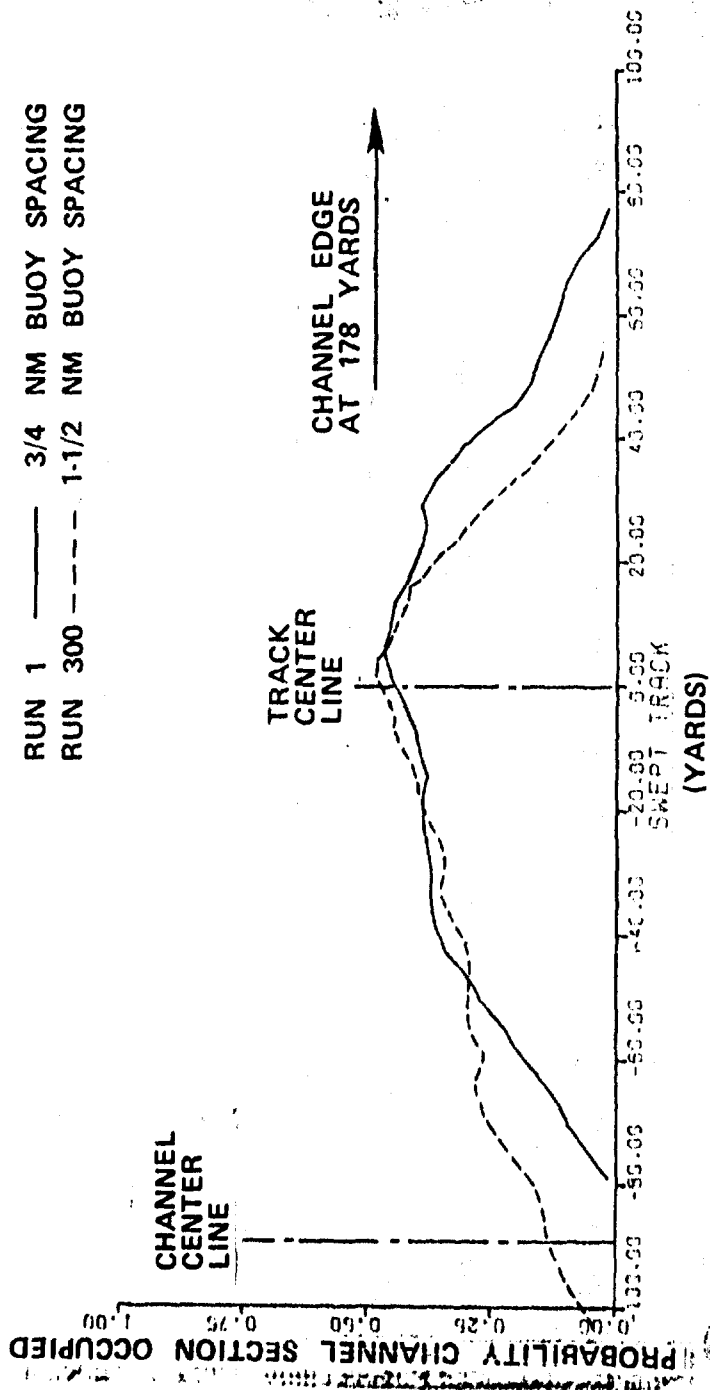
RUN 300  
(533-YARD CHANNEL WIDTH) 1-1/2 NM BUOY SPACING

FIGURE 5-7. TRACK PLOTS, FOUR MONTE CARLO CASES, CLEAR VISIBILITY





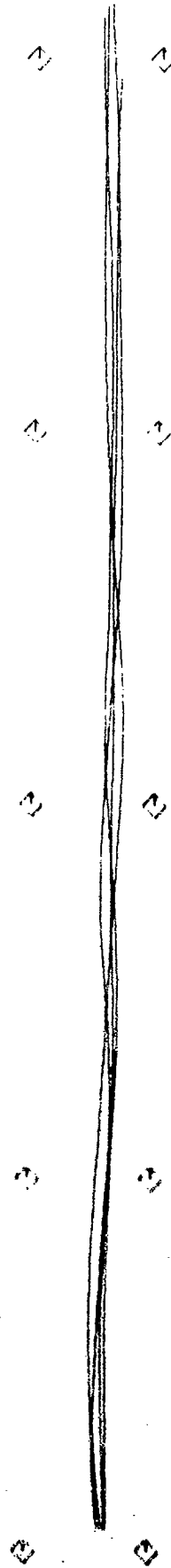
RUN 1 ——— 3/4 NM BUOY SPACING  
 RUN 300 - - - - 1-1/2 NM BUOY SPACING



Best Available Copy

FIGURE 5-8. ACCUMULATED SWEPT WIDTH DATA FOR ALTERNATE AN CONFIGURATIONS, CLEAR VISIBILITY

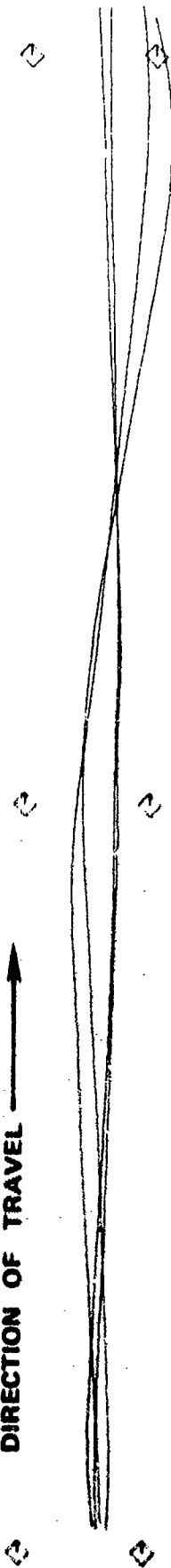
DIRECTION OF TRAVEL →



RUN 150

(533-YARD CHANNEL WIDTH) 3/4 NM BUOY SPACING

DIRECTION OF TRAVEL →



RUN 202

(533-YARD CHANNEL WIDTH) 1-1/2 NM BUOY SPACING

FIGURE 5-9. TRACK PLOTS, FOUR MONTE CARLO CASES, 1/2-NAUTICAL MILE VISIBILITY

RUN 202 ——— 1-1/2 NM BUOY SPACING  
 RUN 150 - - - - 3/4 NM BUOY SPACING

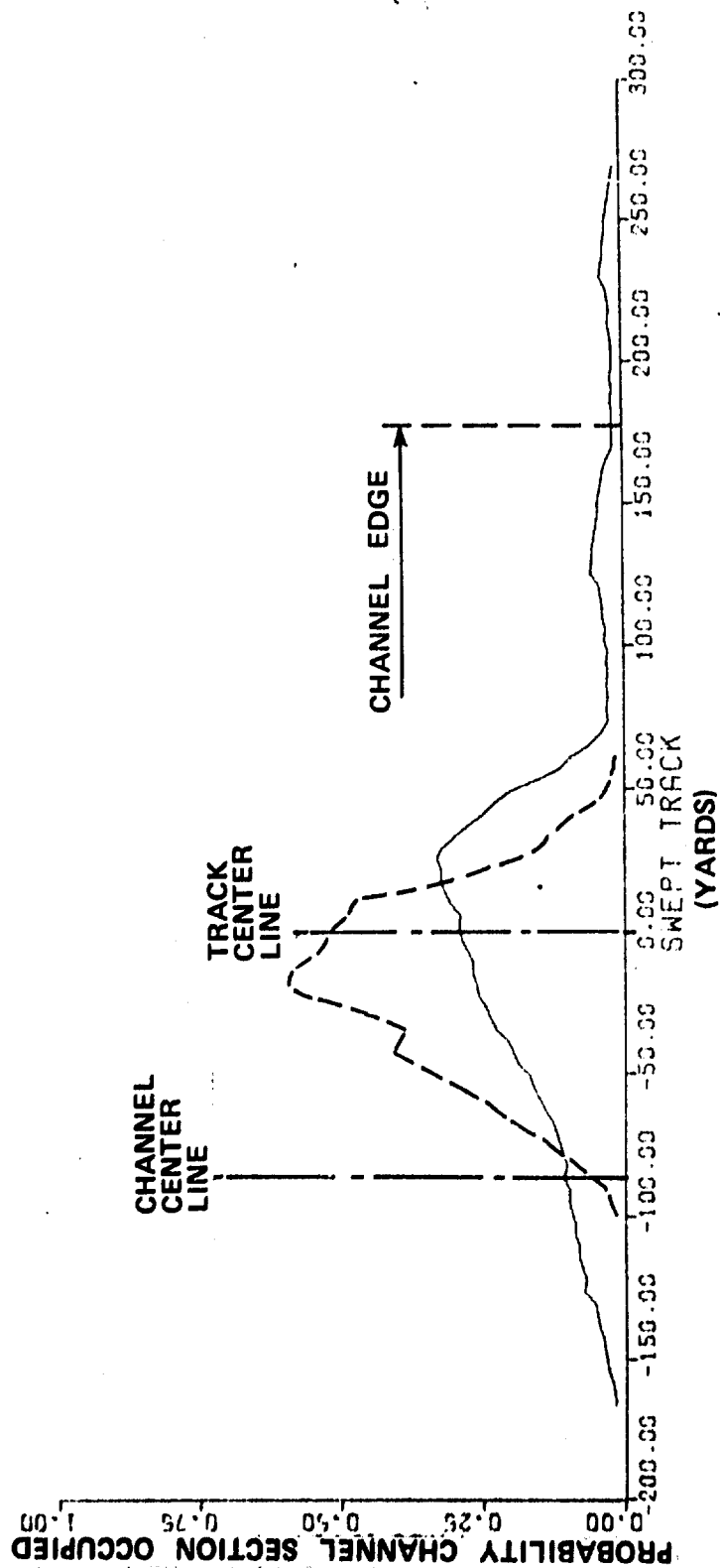


FIGURE 5-10. ACCUMULATED SWEEP WIDTH DATA FOR ALTERNATE AN CONFIGURATIONS, 1/2-NAUTICAL MILE VISIBILITY

Best Available Copy

The output measure of swept width has proven sensitive to the AN configuration in combination with weather conditions.

### 5.2.3 Sensitivity of Traffic Capacity Model

Harbor traffic capacity can be affected by changes in ANs. For example, a reduced probability exists that faster ships will be delayed by slower vessels if vessel passing areas can be extended. This hypothesis was tested in a sample case study where a no-passing zone in a channel (e.g., a turn or narrow portion of channel) was better marked with ANs to aid in passing in the zone.

FIGURE 5-11 illustrates a 10,000-yard channel with a 1000-yard restriction where two-way traffic is not permitted. Individual vessel delays for an arrival rate of 0.1 vessels per minute are plotted in FIGURE 5-12. The high delay rates of the higher speed vessels are a function of their delay in waiting for the restriction to clear. In comparison, data in FIGURE 5-13 illustrate vessel delay times if the 1000-yard restriction is removed to permit two-way traffic along the entire channel. A reduction in delay time for the faster vessels is apparent in these data. The residual delay time in FIGURE 5-13 was caused by a restriction that no vessel was permitted to overtake and pass another vessel.

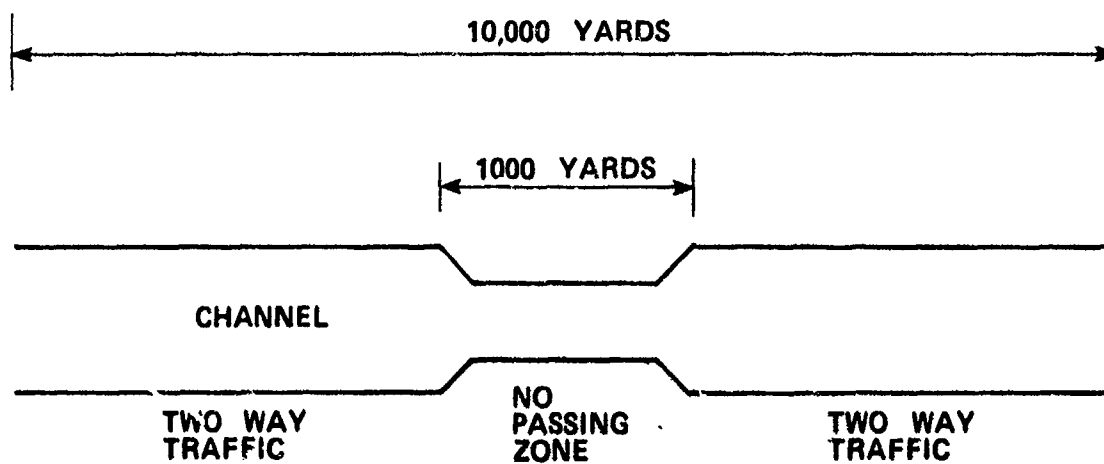
Traffic delay, as a measure of effectiveness, is sensitive to change in traffic flow caused by changing ANs. However, in order of magnitude, channel design (i.e., width, depth, turn radius) probably controls channel capacity more than AN considerations. ANs will contribute to port traffic capacity to the extent that ANs give passing ships position information and thus aid and encourage safe passing. AN change will have a greater impact in reduced visibility conditions.

## 5.3 DEMONSTRATED FLEXIBILITY OF THE AN PERFORMANCE MODELS

A stated requirement for AN performance models specified that they be used easily across a broad range of navigational problems, including changes in geographic areas, in ANs used, in navigation techniques (electronic versus visual fixing), and in fix frequency. The flexibility was demonstrated by modeling two separate locations in U.S. waters and one scenario from CAORF. All differ in navigational processes and maneuvering criteria used.

The following scenarios were selected: coastal passage along the Florida Keys, a 1000-ft channel in the Delaware Bay, and 500-ft channel in the CAORF restricted waterways experiment. Two of these scenarios use radar for fixing; one uses only visual perception for fixing. Fix frequency varies between scenarios from once every 60 seconds and once every 3 minutes to occasions when only ANs are abeam. The track-line band varies from  $\pm 1/4$  miles to  $\pm 75$  feet depending on the scenario.

In each of these areas, navigation processes are the norm at sea. This has been documented in the at-sea data bases at Eclectech Associates. Any other areas could have been selected for demonstration including areas not covered in our data bases. At the present time, our data bases are sufficiently comprehensive to project how ANs and RAs will be used in all east coast U.S. waters.



**FIGURE 5-11. TRAFFIC RESTRICTIONS IN A STRAIGHT CHANNEL**

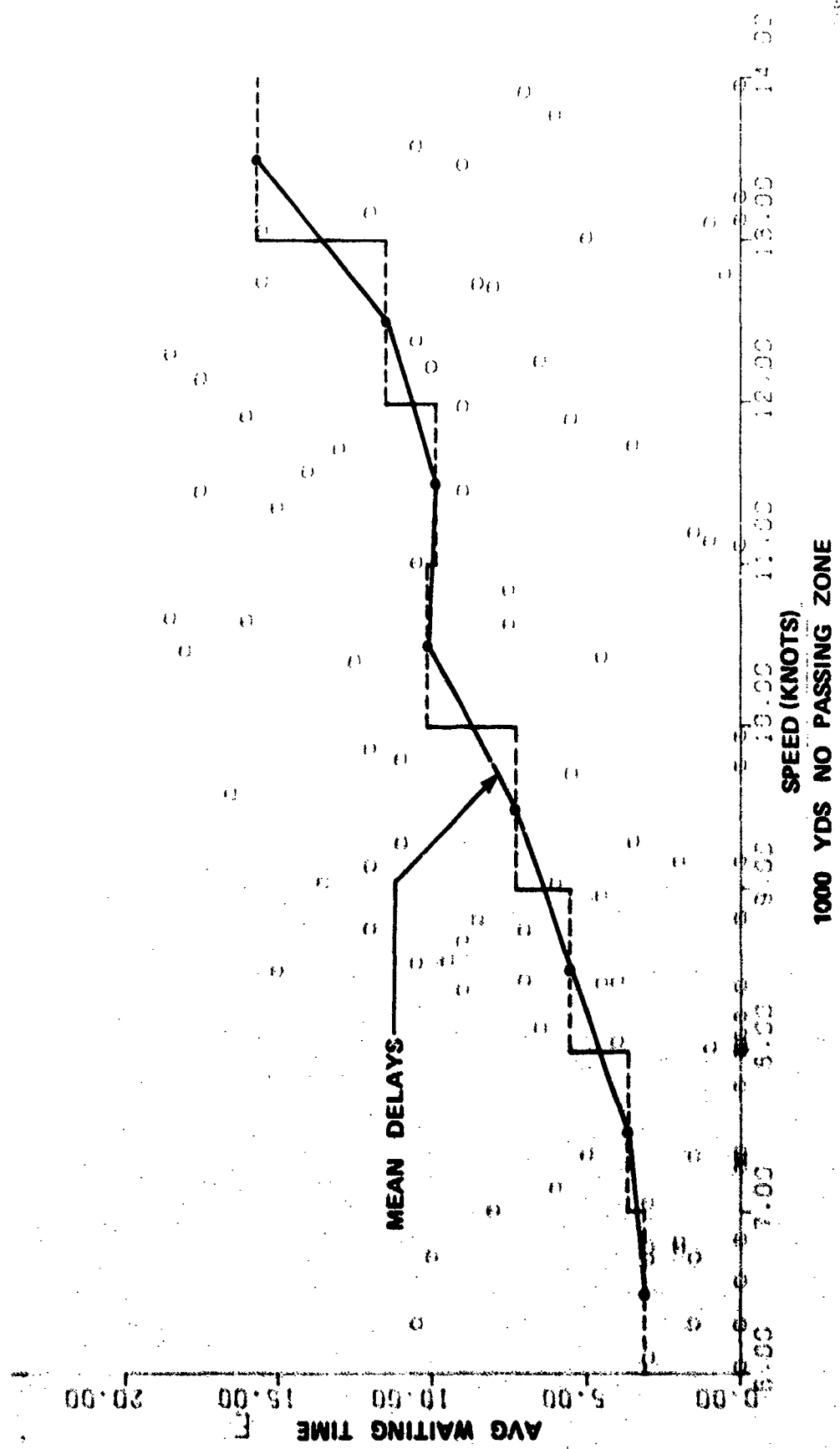


FIGURE 3-12. VESSEL DELAY TIMES WITH PASSING RESTRICTIONS

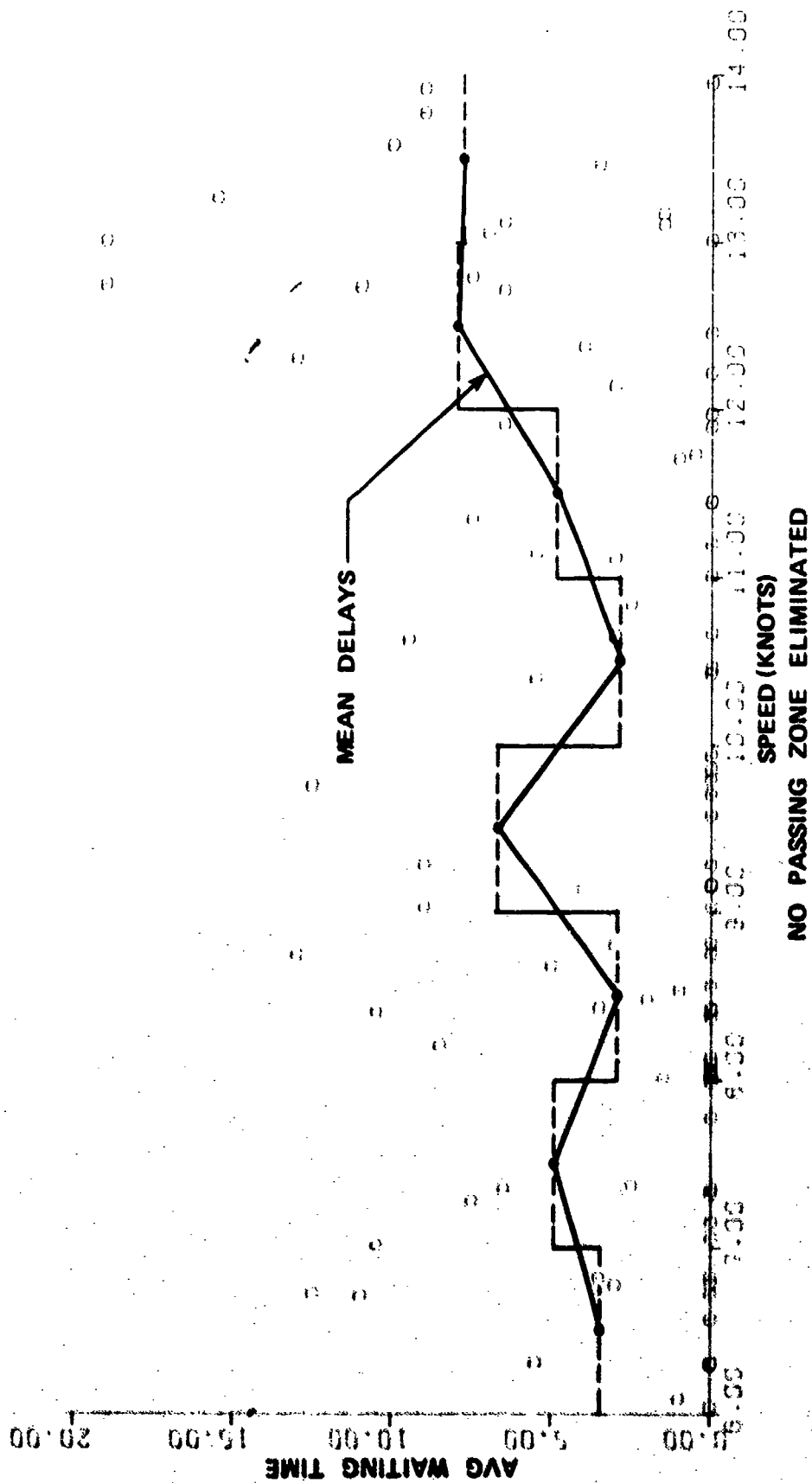


FIGURE 5-13. VESSEL DELAY TIMES WITHOUT PASSING RESTRICTIONS

### 5.3.1 Sample Scenario Evaluation: Florida Keys

A sample coastwise passage between Carysfort Reef and Tennessee Reef was simulated in the model. Ownship was headed southbound maintaining a track 2 nautical miles  $\pm 1/4$  nautical mile off the line of ANs marking the shoal areas. FIGURE 5-14 shows this geographic area and the ship's intended track line. The navigation behavior in this area shows that navigation fixes were taken only when abeam of principal reefs with beacons. A computer listing of our data base in FIGURE 5-15 indicates the mate's typical behavior in this area. These data show that beam radar fixes were taken at Pacific and Molasses Shoals. A course change was made following the beam fix at Molasses Shoals.

The model scenario does not attempt to replicate the at-sea voyage. However, basic behavior is replicated. Radar range and bearing fixes are taken whenever a fixed reef structure is abeam. When Molasses Shoals is detected abeam, a course order is given. If the ship is considered to be more than  $1/4$ -mile off track, a corrective heading is ordered. Heading changes are ordered only after the position has been determined by a beam fix.

Track curves for three Monte Carlo runs in this scenario are illustrated in FIGURE 5-16. The navigation process as defined in the model and the spacing of the ANs have apparently allowed safe navigation in this area. Full evaluation of this scenario would include additional replications of these runs and runs in adverse wind and current conditions. Vessels of various speeds should also be tested to determine if ships can approach shoal areas when they make a large error in their dead reckoning.

### 5.3.2 Sample Scenario Evaluation: Miah Maull Range Channel, Delaware Bay

This scenario evaluation was conducted in the lower Delaware Bay channel. (See FIGURE 5-17.) The Miah Maull range section of the channel was selected as a representative channel in this area. Channel width is 1000 feet. Available aids include Miah Maull shoal light, an abandoned light tower, cross ledge light, and a series of buoys spaced approximately 3 nautical miles apart.

The primary fix method used along Miah Maull range is radar ranges abeam to the fixed towers and beacons. Between these, the distance from the ship's projected path to the aids is estimated by aligning the radar cursor to ship's heading flash. Fixes are generally taken only when abeam or at 3- to 5-minute intervals.

The navigational behavior observed at sea was simulated in the model by performing bearing and range fixes every 3 minutes. Although this does not exactly replicate the process the pilot uses, it does provide the model with the proper order of magnitude for fix errors. Data in FIGURE 5-18 show the track plots derived for this scenario. Generally, they agree favorably with at-sea data. FIGURE 5-19 shows the cumulative swept width for the four track plots. FIGURE 5-20 compares a single Monte Carlo run with the single run along Miah Maull Channel recorded at sea. Maximum swept widths compare within 20 yards. However, the at-sea data indicate that the ship at sea had been allowed to set to the starboard channel boundary because there was no chance of grounding along that side of the channel.

Complete evaluation of ANs in Miah Maull Channel would involve additional runs with alternate sized vessels and extreme conditions of wind and current. Night operation would have differed little from day since the main navigational aid was radar.



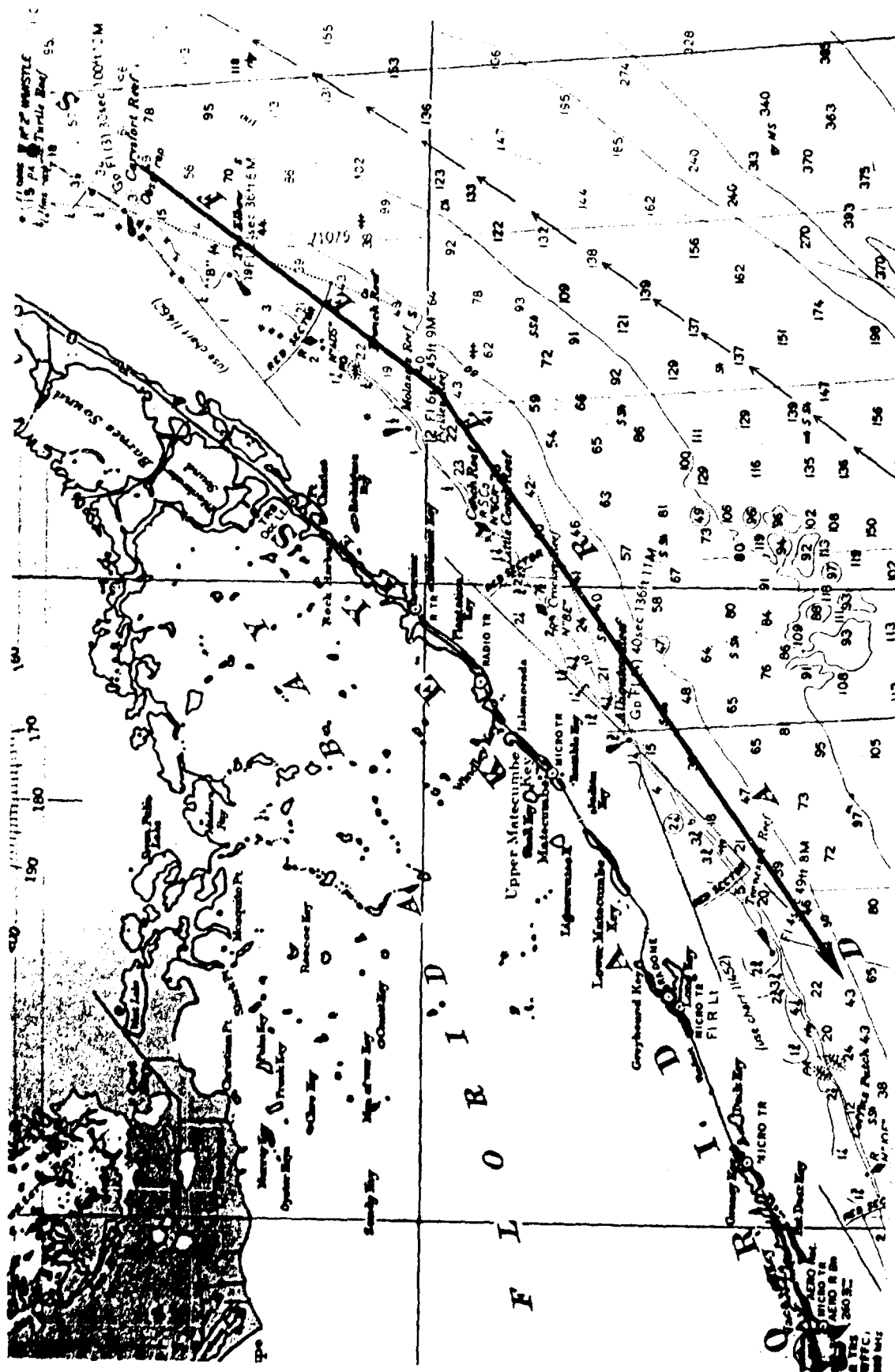


FIGURE 5-14. SAMPLE SCENARIO EVALUATION, FLORIDA KEYS

# TIME

12,341,1855, 15,1, 6, S.P. PHONE TO CAPT. LIGHTHOUSE DARK ← FOWEY ROCKS  
~~12,341,1909, 5,1,30, BOWLOOKOUT. 2 BUZZ. PORT CONTACT~~  
 12,341,1916, 60,1,38, DELETE TWO CONTACTS CAS  
~~12,341,1920, 5,1,30, BOWLOOKOUT. 2 BUZZ. PORT CONTACT~~  
 12,341,1920, 30,1,19, STEER 192 DEG FROM 181  
~~12,341,1924, 60,1,16, MONITOR KEYS AND BUOYS AHEAD~~  
 12,341,1930, 0,1, 0, ABEAM TRIUMPH REEF ← TRIUMPH REEF  
~~12,341,1943, 5,1,30, BOWLOOKOUT. 2 BUZZ. NOT ON RADAR~~  
 12,341,1943, 60,1,34, ACQUIRE 1 CONTACT CAS  
~~12,341,1944, 30,1,41, WATCH CONTACTS ON CAS~~  
 12,341,2000, 60,3,24, MATES CHANGE WATCH  
~~12,341,2006, 60,3,17, MAKE COURSE 199 DEG FROM 192~~  
 12,341,2016, 30,3,13, MATE SIGHTS PACIFIC REEF ABEAM ← PACIFIC REEF  
~~12,341,2016, 10,3,14, DETERMINE RADAR RANGE TO REEF~~  
 12,341,2016, 20,3,15, PLOT FIX IN CHART ROOM  
~~12,341,2049, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT AHEAD~~  
 12,341,2050, 170,3,34, FAIL TO ACQUIRE CAS CONTACT  
~~12,341,2053, 15,3,31, REFLECTION PLOT ONE CONTACT~~  
 12,341,2054, 15,3,16, RADAR WATCH  
~~12,341,2054, 20,3,34, FAIL TO ACQUIRE CONTACT CAS~~  
 12,341,2100, 10,3, 4, MATE LOOKOUT W BINOCULAR  
~~12,341,2102, 5,3,16, ASSESS RADAR~~  
 12,341,2102, 39,3,34, FAIL TO ACQUIRE CONTACT CAS  
~~12,341,2103, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT PORT~~  
 12,341,2107, 15,3, 4, BINOCULAR LOOKOUT  
~~12,341,2107, 10,3,16, RADAR WATCH~~  
 12,341,2108, 65,3,35, ACQUIRE TWO CONTACTS CAS  
~~12,341,2118, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT PORT~~  
 12,341,2121, 12,3,16, WATCH RADAR  
~~12,341,2125, 60,3,34, ACQUIRE CONTACT TO PORT~~  
 12,341,2134, 60,3,13, WAIT TILL BUOY ABEAM  
~~12,341,2134, 15,3,14, RADAR RANGE TO BUOY~~  
 12,341,2135, 60,3,19, STEER NEW COURSE 234 DEG ← MOLASSES SHOAL  
~~12,341,2136, 50,3,15, PLOT FIX ON MOLASSES SHOAL~~  
 12,341,2137, 240,3,18, STUDY CHARTS  
~~12,341,2150, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT PORT~~  
 12,341,2155, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT PORT  
~~12,341,2207, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT PORT~~  
 12,341,2208, 5,3,30, BOWLOOKOUT. 2 BUZZ. CONTACT PORT

Best Available Copy

FIGURE 5-15. COMPUTER LISTING OF DATA BASE

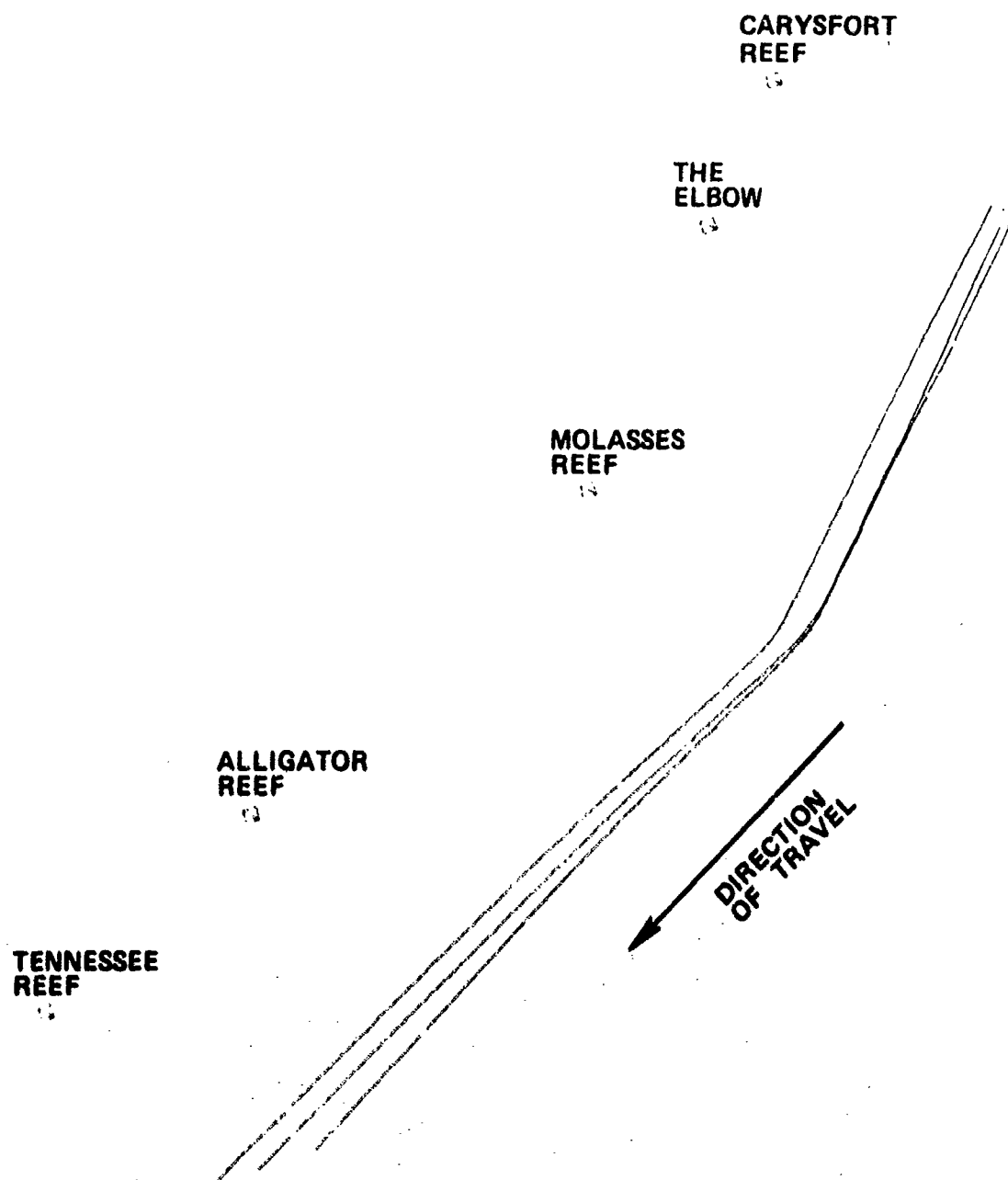


FIGURE 5-16. TRACK CURVES FOR THREE MONTE CARLO RUNS, FLORIDA KEYS

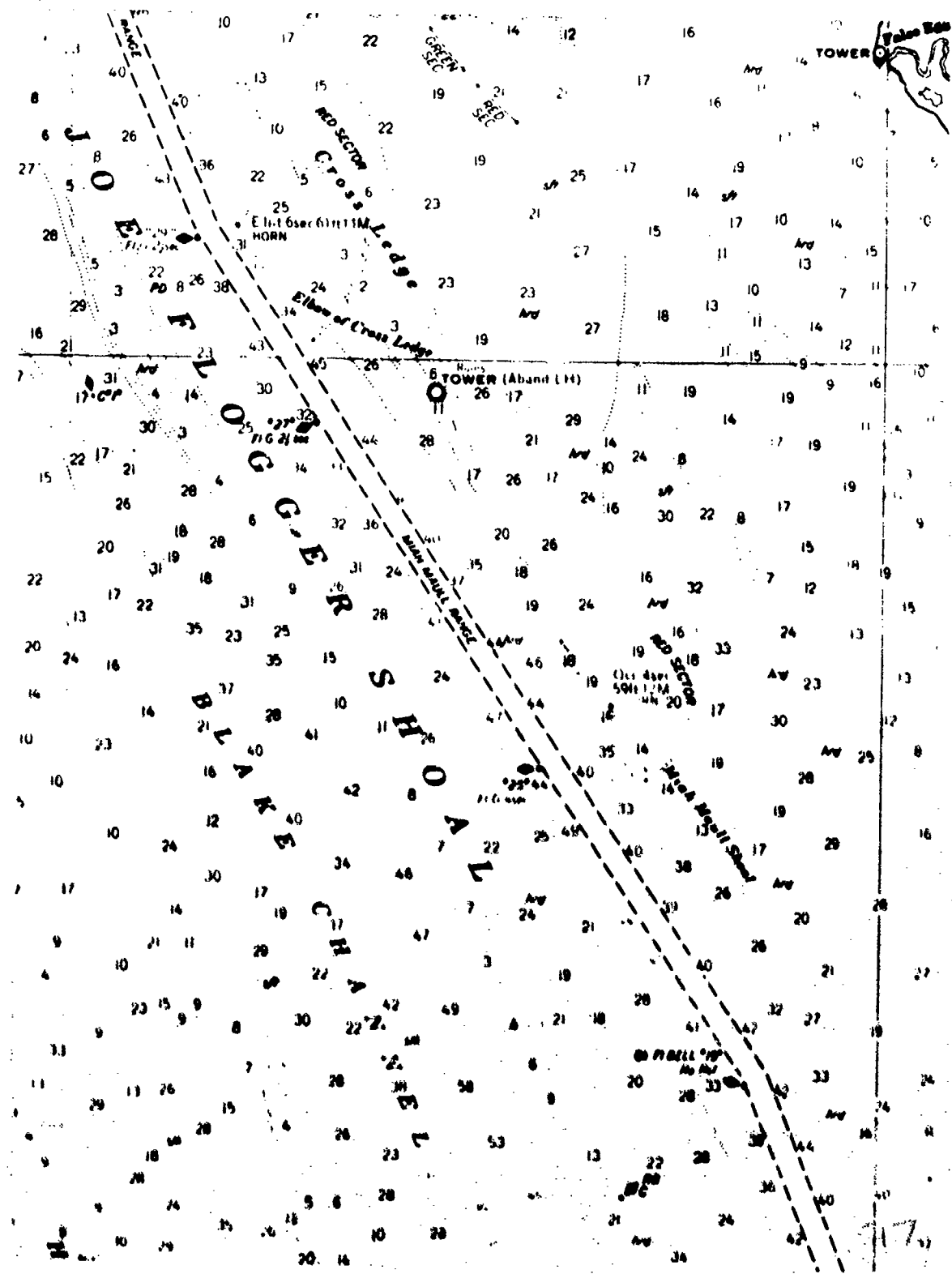


FIGURE 5-17. MIAH MAULL RANGE CHANNEL, DELAWARE BAY

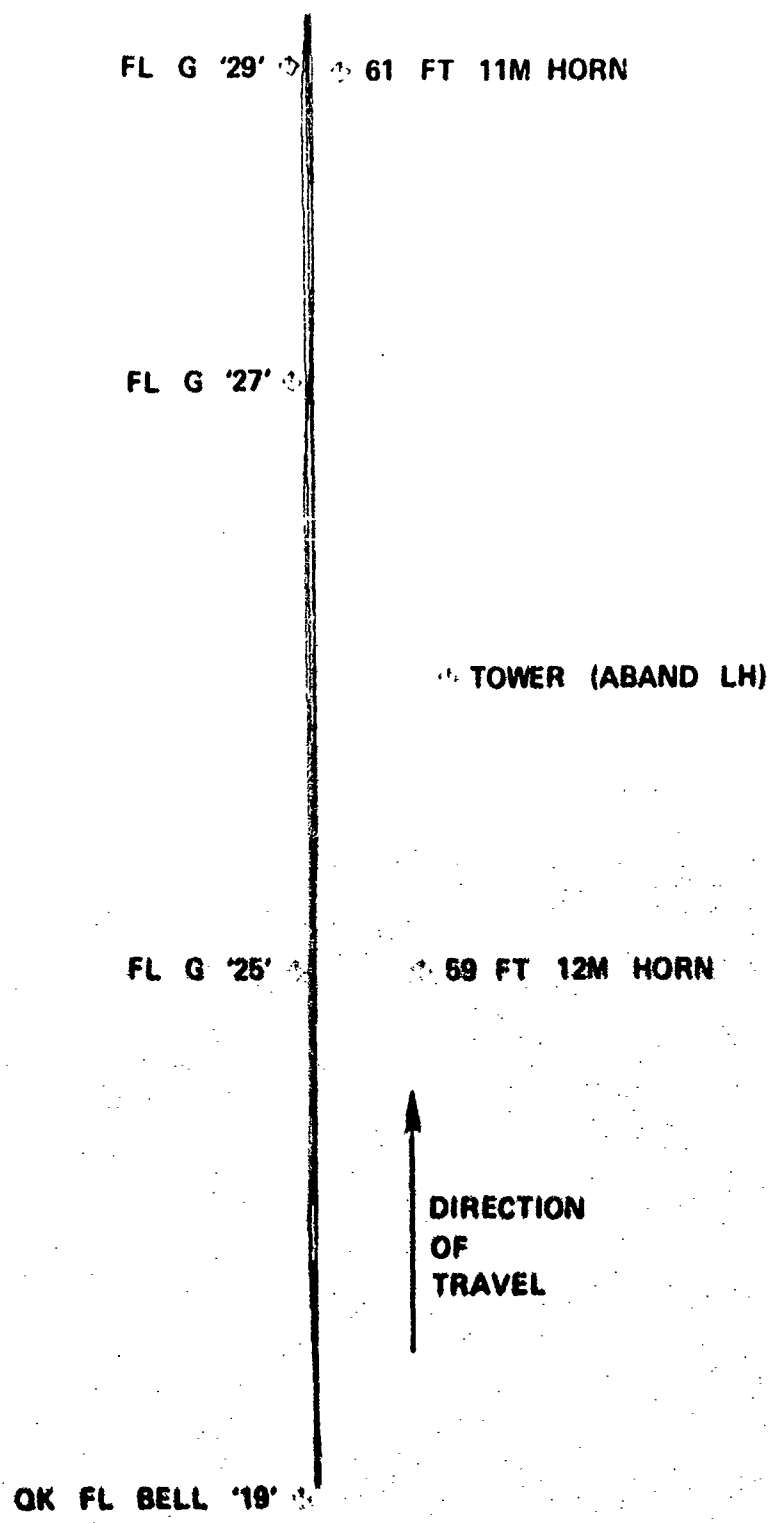


FIGURE 5-18. TRACK PLOTS FOR MIAH MAULL RANGE CHANNEL SCENARIO

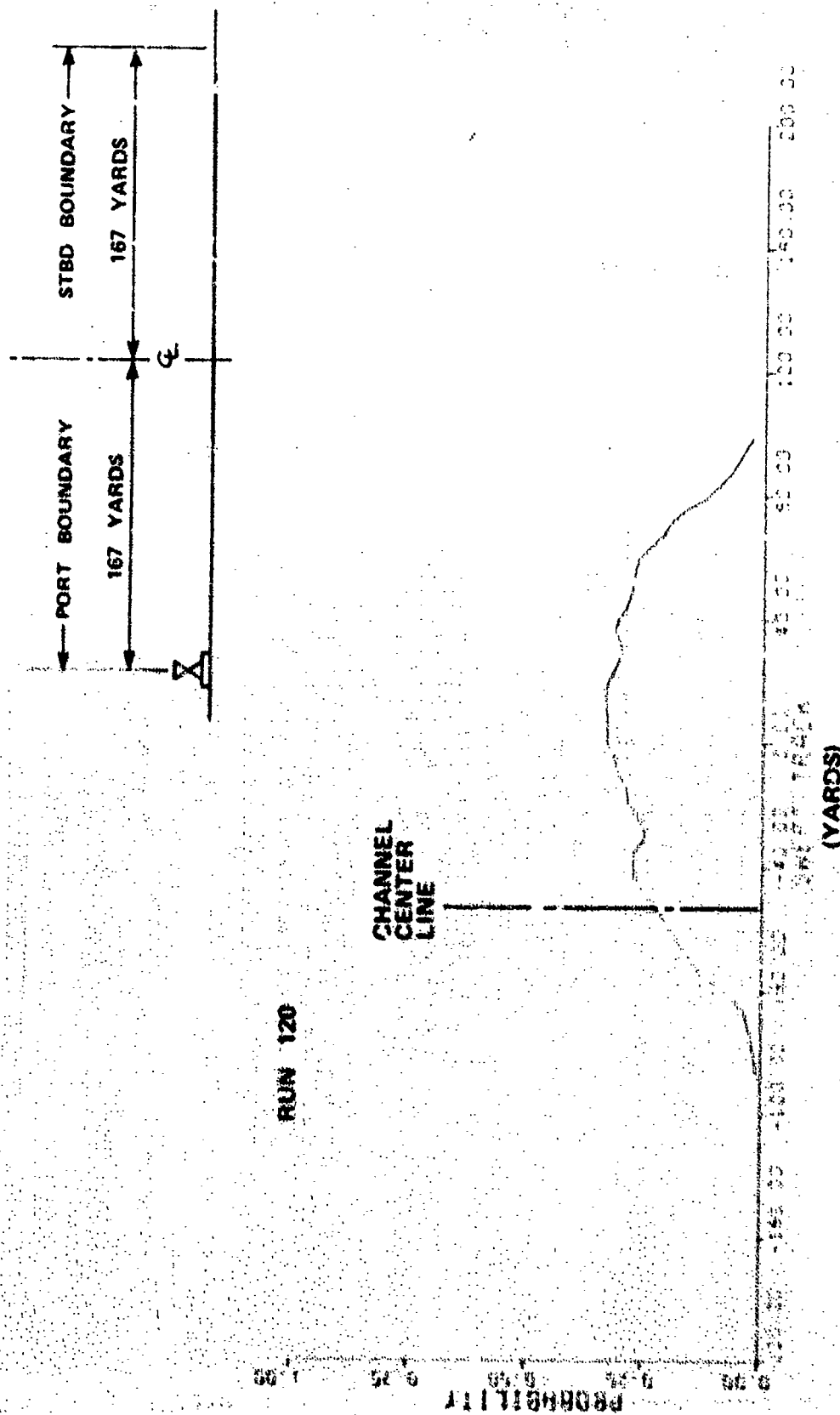
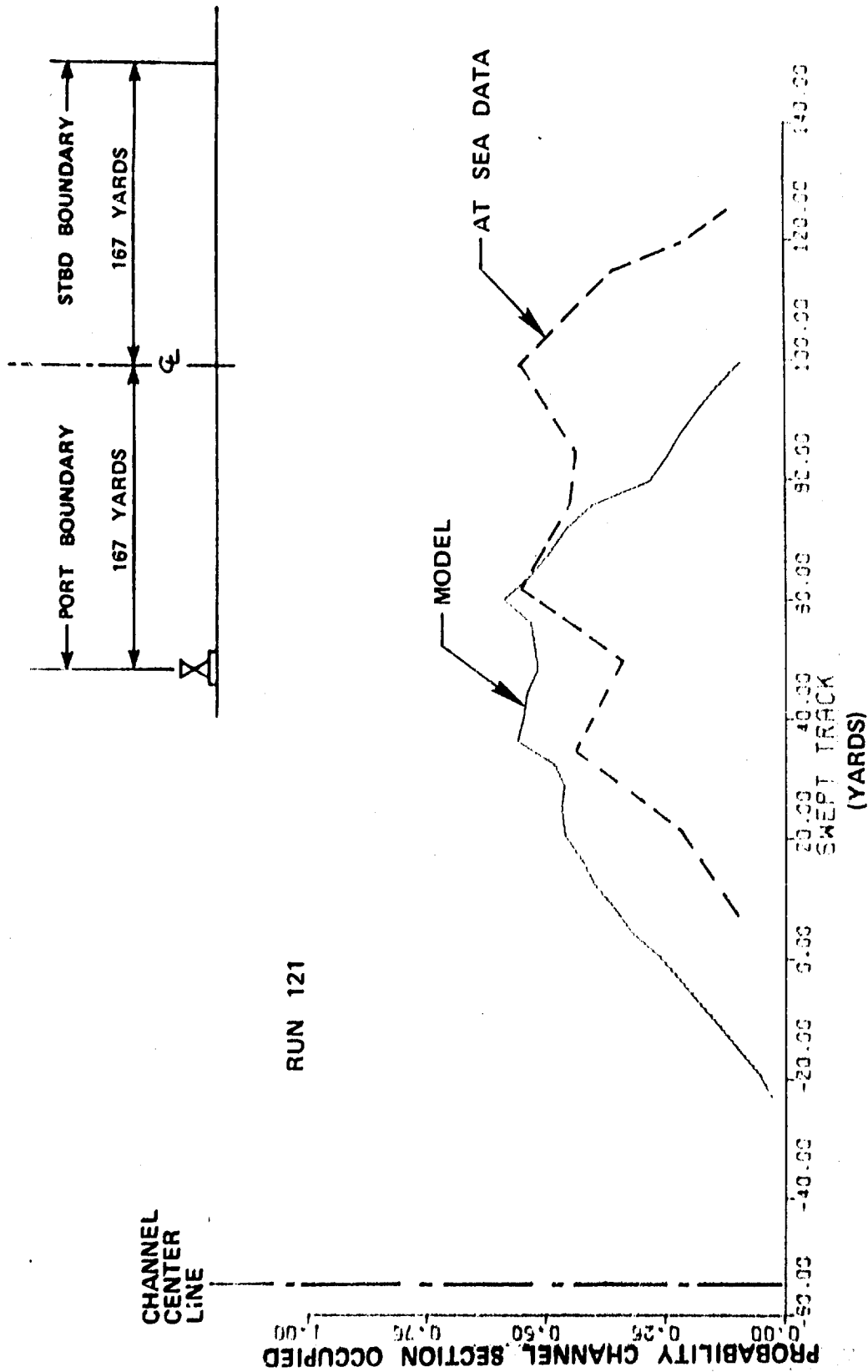


FIGURE 5-19. CUMULATIVE SWEEP WIDTH MODEL DATA IN MIAH MAULL RANGE



Best Available Copy

FIGURE 5-20. CUMULATIVE SWEPT WIDTH FOR A SINGLE TRACK RECORDED DURING AT SEA DATA COLLECTION

### 5.3.3 Sample Scenario Evaluation: CAORF Restricted Waterways

The final sample scenario evaluated was a portion of the restricted waterways channel as designed for the recent MARAD and USCG sponsored studies at CAORF. FIGURE 5-21 shows the AN configuration and the 2-nm channel section evaluated. The channel is 500 feet wide, marked only with gated buoys near the corners and at the mid-legs. Pilots were required to navigate by visual fixing techniques alone (no pelorus).

Navigation in this scenario was modeled by allowing the pilot to take visual fixes every 60 seconds. The track plots in FIGURE 5-22 illustrate the success of navigating the second leg of the channel in the daytime with no wind or current. Cumulative swept width data from these model runs agree favorably with data derived from the track plots of CAORF runs released by the Coast Guard. Data curves in FIGURE 5-23 compare the swept width curves of the CAORF data with the model data. The maximum values and shapes agree with an error of only 10 yards. This is believed to be well within the normal variance of the two sets of data. Further analysis of the CAORF data tapes will allow an accurate comparison between model and CAORF data.

## 5.4 MODEL VALIDATION

True validation of the models requires that they reasonably match the real world and are able to interpolate between and extrapolate beyond the existing data bases. All preceding examples in this section have demonstrated that the AN performance models may be valid tools for the study of ANs by the Coast Guard. The models are sensitive to changes in AN configurations; they have the flexibility to evaluate a broad range of navigational processes requiring the use of both ANs and RAs.

At this time, there are few data bases in the world which document the performance of ANs at sea. A major recommendation of our report is that a comprehensive at-sea and simulator data collection program be initiated in Phase II of this program (see Section 6). These efforts will provide the foundation for model use and for future improvements in ANs and RAs. One of the data bases available, however, is that presently being compiled at CAORF in the restricted waterways experiment. This data base has provided the initial opportunity to validate our models.

### 5.4.1 Validation of Visual Perception Fixing Routines

The most difficult task of the AN models will be to provide an accurate model of the fix accuracy obtained using only visual perception. Quantification and modeling of errors in electronic fix methods, and interpolation and plotting errors, is an order of magnitude less difficult than quantifying and modeling the complex process of estimating own ship's position by looking at a number of ANs. Generally speaking, electronic fix information (radar, pelorus, LORAN, etc) consists of just two or three lines of position, the errors of which can be quantified (TABLE 4-1, Section 4). The potential error of these fixes is calculated by a number of maximum probability techniques (see Appendix A). On the other hand, visual fixing may involve mentally crossing many lines of position dependent on visual estimation of bearings and ranges to aids. The question becomes how to best represent the process to ensure validation.

To guarantee validity, our visual fix routines were based on empirically derived relationships for range lights. Generally speaking, we calculate a fix solution from





FL R  
FL G

FL R  
FL G

FL R  
FL G

FL R  
FL G

— DIRECTION OF TRAVEL —

FIGURE 5-22. TRACK PLOTS FOR CAORF RESTRICTED WATERWAYS

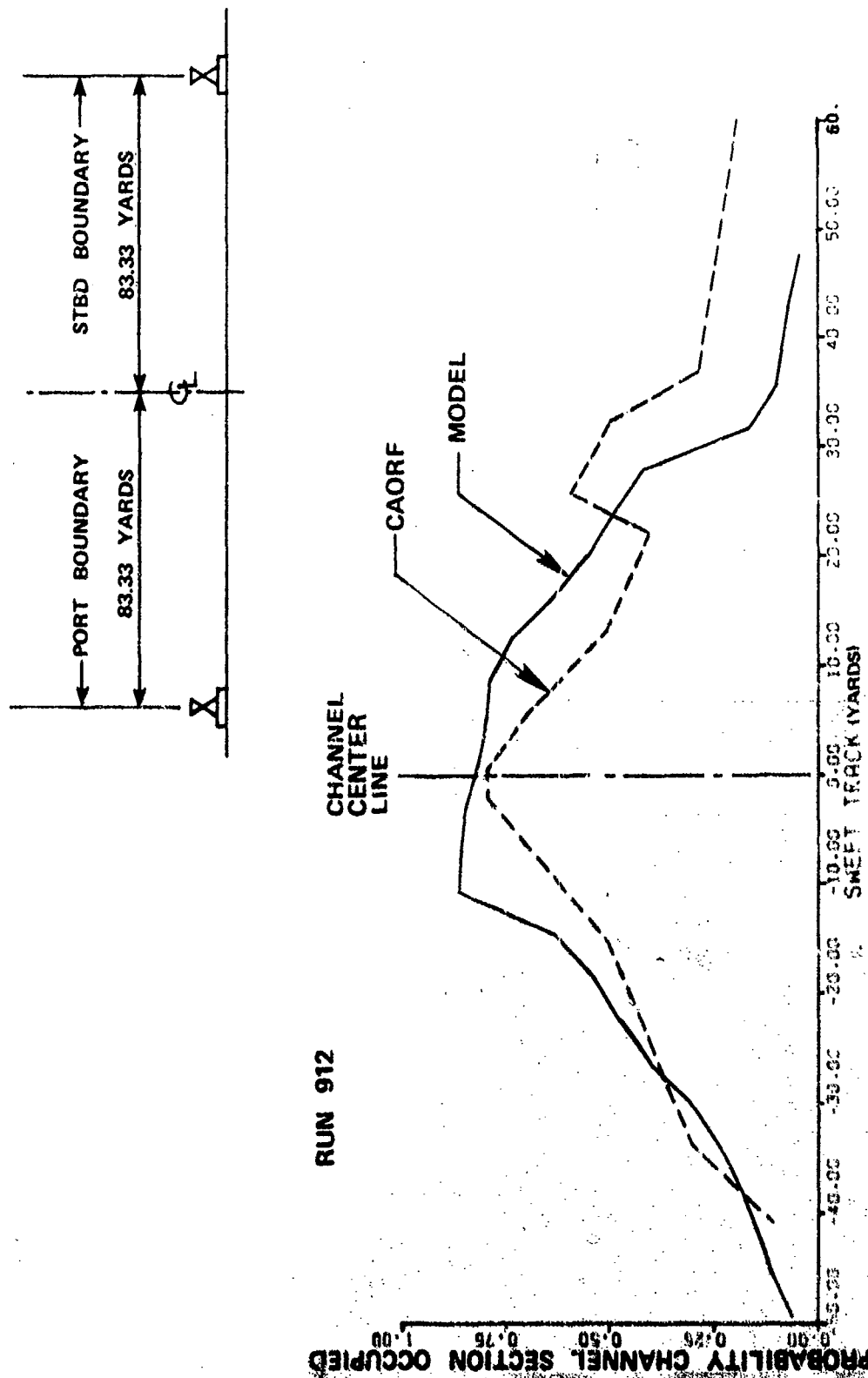


FIGURE 5-23. ACCUMULATED SWEPT WIDTH DATA FOR RESTRICTED WATERWAYS CHANNEL, MODEL DATA VERSUS CAORF DATA, CUTOFF TURNS WITH MID-LEG BUOYS

visually estimated bearings and ranges. The key to the accuracy of this process is correlation of bearing errors for those aids observed at nearly the same relative bearing. This correlation process (i.e., reducing the bearing for certain aids close in relative bearing) depends on the vertical and horizontal angle between aids.

After review of fix data recently released from CAORF, it appears that our approach is a valid one. The standard deviation of position estimation errors measured at CAORF and predicted by our model fix estimation routines are of the same order of magnitude value and demonstrate similar trends for distance from ANs.

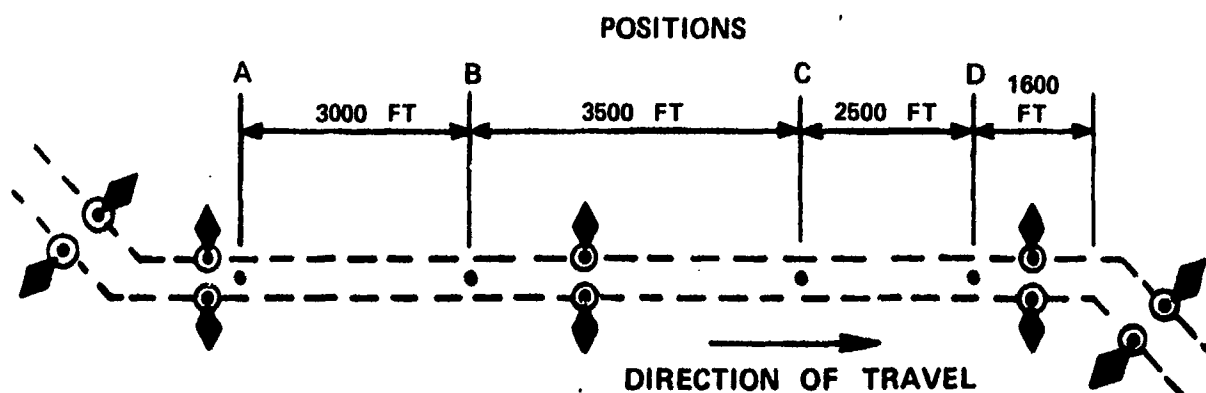
Data in FIGURE 5-24 compare the CAORF static fix data to static fix data from our model. Four positions were evaluated along the channel with cutoff corners and mid-leg buoys. The error distribution for visual estimation of bearings was used in the model. The standard deviations for cross track position estimation were calculated with and without the correlation of bearing errors.

Those calculated with correlated bearing errors use observed bearings which have been adjusted to account for the relationships between vertical and horizontal angles to all buoys. Those calculated without correlated bearing errors use observed bearings taken straight from the observation error distributions. Data calculated with correlated errors provide an order of magnitude fit to the data measured at CAORF. The standard deviation reduced when the ship is further back from the mid-leg gates, position A versus position B (CAORF 11 feet versus 29 feet and model correlated 7 feet versus 38 feet). Such a relationship is described by the range light equations. Data calculated with uncorrelated errors follow none of the trends of the CAORF data and differ in some cases by many orders of magnitude (position A CAORF 11 feet versus model uncorrelated 113 feet).

Further validation of the model's visual perception routines can be seen in FIGURE 5-25. Here, the mid-leg gate buoys have been removed. Data in the table indicate that the model operating with correlation achieves an excellent match of CAORF data for points A and B. The model without correlation fails to match the trend of the data and is incorrect by several multiples. The lower value for the position errors at point A is explained by the fact that buoys 6 and 7 become nearly in line at this position.

One additional test was performed to validate the visual fix routines. Nine random position fixes were drawn from the model's fix estimation routines for a point which had been used at CAORF. FIGURE 5-26 shows a comparison of the absolute values of errors in cross track position estimation. The CAORF data, representing independent static fixes by nine pilots, compares favorably to those output by the model.

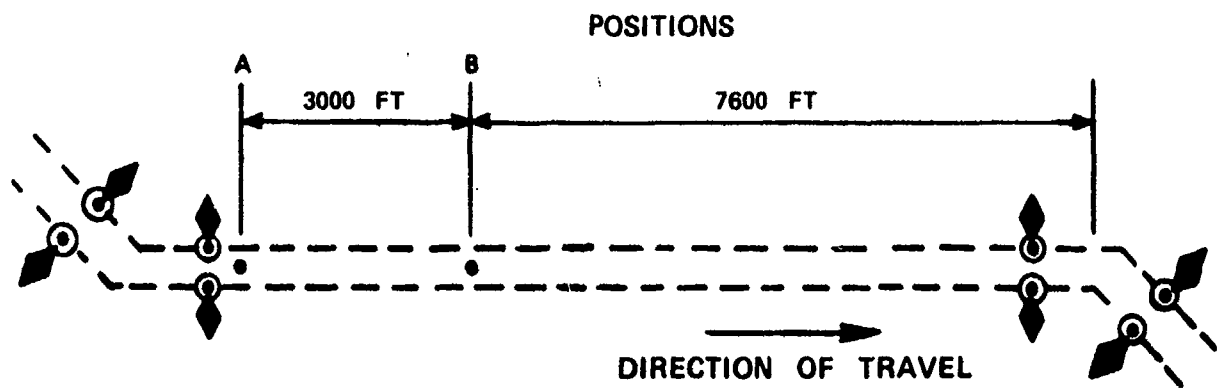
Total validation of the visual fixing routines require that more at-sea and CAORF data be compiled across many AN configurations and environmental conditions. However, comparison of data in FIGURES 5-24 through 5-26 indicates that the model now provides a valid representation of a limited example. The agreement of these data provides validation for our approach of using bearing error distributions measures at CAORF for the main error driving function, then correlating bearing errors between certain aids as they achieve unique or advantageous alignment.



**STANDARD DEVIATION OF  
CROSS TRACK POSITION  
ESTIMATION ERRORS (FEET)**

ORDER OF MAGNITUDE MATCH	POSITION			
	A	B	C	D
CAORF DATA	11 FT	29 FT	55 FT	56 FT
MODEL WITH CORRELATION	7	38	28	70
MODEL WITHOUT CORRELATION	113	60	103	62

**FIGURE 5-24. VALIDATION OF VISUAL FIX ESTIMATION, CAORF RESTRICTED WATERWAYS CHANNEL, CUTOFF CORNER WITH MID-LEG BUOYS**

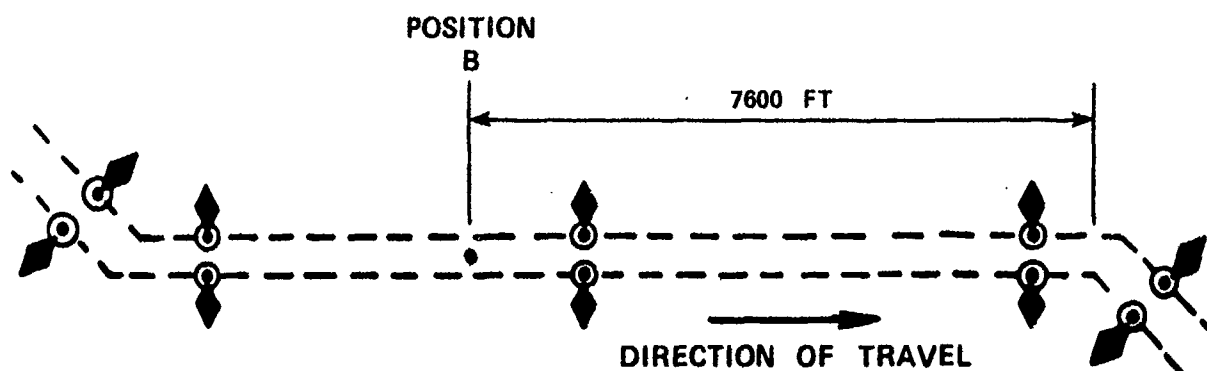


**STANDARD DEVIATION OF  
CROSS TRACK POSITION  
ESTIMATION ERRORS (FEET)**

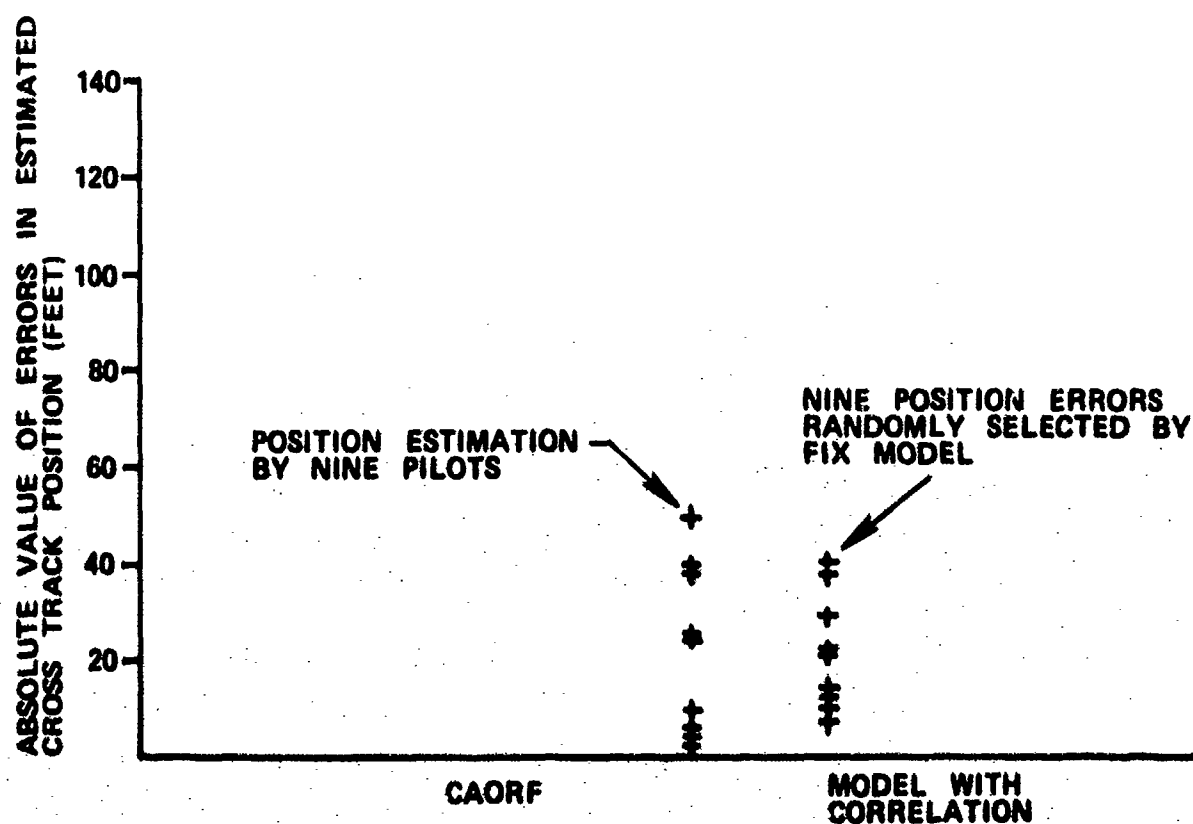
ORDER OF MAGNITUDE MATCH	POSITION	
	A	B
CAORF DATA <sup>1</sup>	61 FT	95 FT
MODEL WITH <sup>1</sup> CORRELATION	60	96
MODEL WITHOUT <sup>1</sup> CORRELATION	160	150

1. ALL DATA REPRESENT AVERAGE OF POSITION ESTIMATION AT TWO POSITIONS, 100 FEET DIFFERENT IN CROSS TRACK POSITION. ALONG TRACK, POSITIONS IDENTICAL.

**FIGURE 5-25. VALIDATION OF VISUAL FIX ESTIMATION, CAORF RESTRICTED WATERWAYS CHANNEL, CUTOFF CORNER WITHOUT MID-LEG BUOYS**



**POSITION B  
CUTOFF CORNERS WITH  
MIDLEG BUOYS**



**FIGURE 5-26. COMPARISON OF RANDOM MODEL FIXES WITH PERFORMANCE OF CAORF SUBJECT GROUP**

#### 5.4.2 Validation of Entire Navigating and Steering Model

The swept width data output by the navigating and steering models provides the major measure of effectiveness related to safety. It is important that data provide a valid representation of similar data available in at-sea or simulator data bases. In the examples described in Section 5.2, we illustrated that the swept width data output by the model is of nearly the same value as data observed at sea (Miah Maull Channel, FIGURE 5-20) and on the CAORF ship simulator (restricted waterways channel cutoff corners with mid-leg buoys, FIGURE 5-23).

The matches between model data and at-sea data are particularly significant because of:

- a. Differences in channel width (Miah Maull -- 1000 feet; CAORF -- 500 feet),
- b. The fix information source (radar versus visual perception), and
- c. The difference in fix frequency (3 minutes versus 1 minute). Across this range of differences, the model generated swept width track plots approximately equal to the data bases.

Total validation of the navigating and steering model will require compilation of at-sea and simulator data with a broad range of ANs, channel designs, and weather conditions. A more detailed analysis of the current CAORF data should provide opportunity in the near future to test the model's ability to predict the experimental results currently under analysis.

The close match of swept width data indicates that the structure and functioning of our navigating and steering model are valid. These matches validate our selected approach of model observable mean processes and sampling from observed distributions about the means in a Monte Carlo model. The decision and action structure of the model proved to be a valid model control feature for modeling responses across a broad range of variables and navigational behaviors.

#### **5.5 OVERVIEW OF MODEL CAPABILITIES AND ACHIEVED GOALS**

Six requirements were initially established for the AN performance models (see Section 2). These were to:

- a. Base model development on observable behavior and measurable performance recorded at sea and on ship simulators.
- b. Provide output measures of effectiveness sensitive to changes in AN variables.
- c. Provide output measures of effectiveness that adequately indicate relative safety and traffic facilitation.
- d. Include validation of the model and its output measures of effectiveness as an implicit part of the model development process.
- e. Design a model capable of evaluating performance of a broad range of ANs in diverse geographic regions.



f. Design a model simple enough for use in AN selection and placement at the district office level, yet sophisticated enough to be used as a valuable research tool at USCG branches in Coast Guard Headquarters.

We met each of these requirements in the development of demonstration models in this study.

The AN performance models use mean process relationships and error distributions measured directly at sea. These include equipment error functions, perceptual differences, and behavioral differences. The processes represented in the model replicate, to the greatest extent possible, processes observed and measured at sea or on ship simulators.

The measures of effectiveness output by the AN performance models have been observed and measured at sea. These measures have proven to be sensitive to changes in AN configurations both at sea (Section 3) and as output variables of the AN performance models (Section 5.2).

The output measures of effectiveness presently appear to adequately represent relatively safety and traffic facilitation. Experience in their use and interpretation will provide guidelines for their future use (Section 5.2).

Compilation of at-sea and ship simulator data provides the key for future model development and validation. Data bases provide the distributions of behavior and perception used by the model; they provide measures of effectiveness for the real world against which to validate and tune model outputs (Section 5.4). The AN performance models developed in this study are guaranteed to be as accurate as available data which describe AN performance at sea today, because they are based on the navigational driving functions observed at sea.

The great flexibility of the models in representing diverse navigation behaviors and use of alternate aids has been derived from the ability to easily change the pilot's decision and action criteria between problems. The extent of the simulation range of the model currently operating was demonstrated by simulating coastwise navigation and navigation in two dissimilar channels (Section 5.2). The model can simulate use of all major ANs and RAs presently under the jurisdiction of the Coast Guard.

Model simplicity has been achieved by synthesizing three smaller models, each dedicated to one measure of effectiveness. This simplifies applications of the models to research problems and reduces computer time required for the derivation of order of magnitude answers at an applied level. Completion of the input syntax translation routines will extend operational capability to many groups in headquarters and district offices.

## Section 6

### PLAN FOR COMPLETION, VALIDATION, AND APPLICATION OF THE AID TO NAVIGATION PERFORMANCE MODELS

#### 6.1 INTRODUCTION

As stated in our original proposal, development of AN performance models in Phase I has proceeded beyond the scope of the USCG task statements. This progress, which was based on our prior knowledge, data files, and modeling technology allows us to project completed development, validation, and application of the model within 4 years from the start of the Phase I effort.

Our goal would be to complete three major tasks in this time period resulting in:

- Establishment of AN and RA requirements
- Evaluation and improvement of an existing harbor
- Establishment of AN performance models on a working basis at Coast Guard Headquarters and district offices.

FIGURE 6-1 gives an overall plan for completing these tasks. The work to be done in each phase is represented by task blocks; the three major tasks will be worked in parallel over the next 3-1/2 years. The following paragraphs give a general breakdown of the work to be completed in each phase.

#### 6.2 PHASE II: AN PERFORMANCE MODEL DEVELOPMENT AND VALIDATION

During the 18-month Phase II effort, model development and validation will be completed. Major at-sea data collection and additional data collection at CAORF are planned to provide a data base for validation and practical insight into how AN requirements should be established in the future. Following at-sea and CAORF data collection, a preliminary effort will be undertaken to establish AN and RA requirements using both the model and available data. A second at-sea data collection effort will be conducted during Phase II. This effort will focus on documenting navigation behavior in a selected harbor which the Coast Guard wishes to improve. The work to be completed in each of these task areas is discussed below. Task numbers correspond to those in FIGURE 6-1.

##### 6.2.1. Task 2.1. Complete Model Development and Validate

Both the fix and piloting model and the navigating and steering model are now in an advanced stage of development. All major subroutines have been programmed and operated in the models. Completing these models requires development of the syntax translator for the action and decision statements and refinements of the subroutines. The traffic model, developed to only a low level of sophistication in Phase I, will require further development of the subroutines. The syntax translator used for the navigating and steering model is planned for use in the traffic model.

All model subroutines will be refined and validated as data become available from the CAORF studies and the at-sea data base. Validation will consist of the ability to statistically match CAORF, at-sea, and model data.

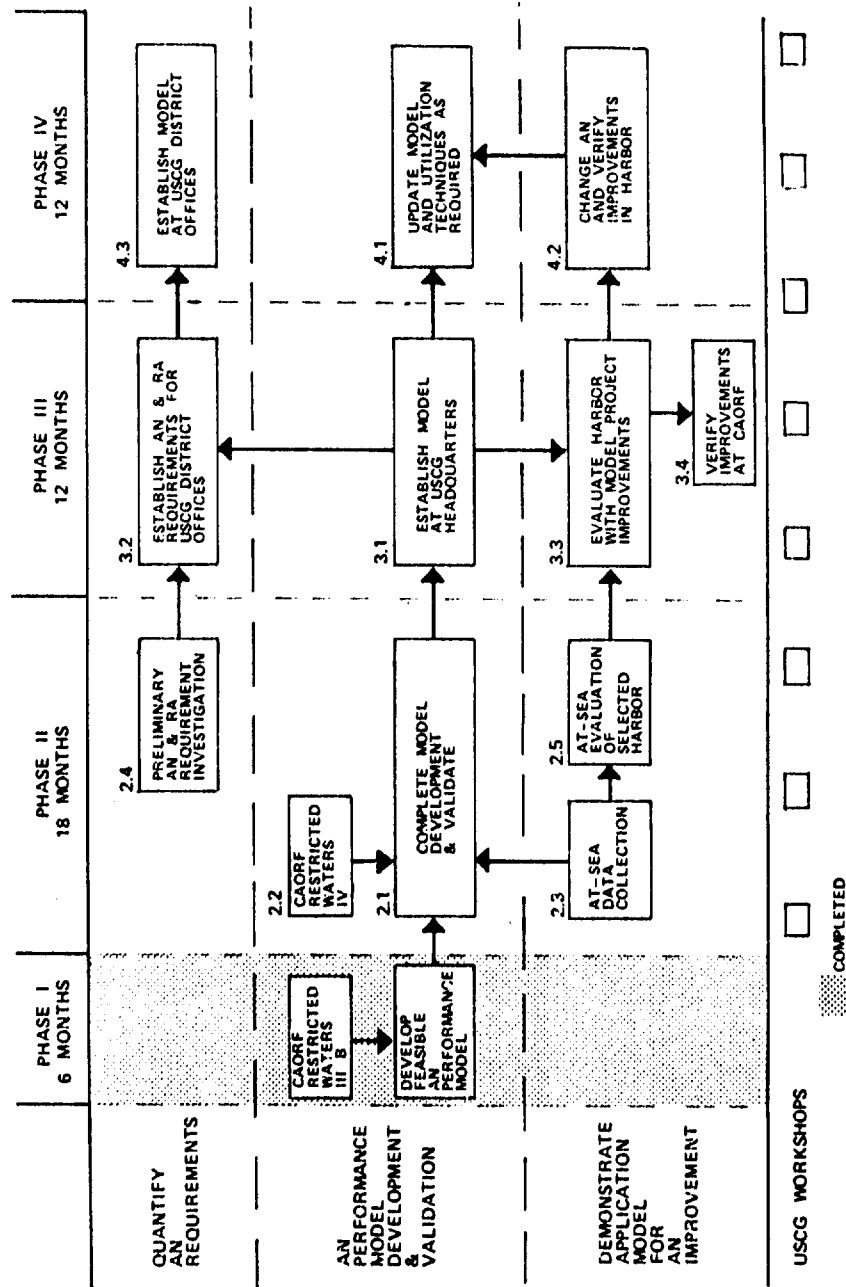


FIGURE 6-1. PLAN FOR COMPLETION, VALIDATION, AND APPLICATION OF AN PERFORMANCE MODELS

Best Available Copy

All models will be documented in their final form for delivery to the Coast Guard.

#### **6.2.2 Task 2.2. Conduct CAORF-Restricted Waterways IV Experiment**

We recommend that the Coast Guard pursue one additional experimental effort in support of AN performance model development. The purpose of this experiment would be to test nighttime and limited visibility navigational performance. Data available from USCG restricted waterways experiment IIIB are expected to adequately cover daytime navigation. Also proposed is a comprehensive experiment for testing piloting fix accuracy. This experiment costs less than dynamic runs and will provide valuable validation data for the fix models. Daytime, night, and limited visibility fix accuracy should be exhaustively tested.

#### **6.2.3 Task 2.3. Collect Data at Sea**

We recommend compilation of a comprehensive and accurate data base to document navigation performance relative to available ANs and RAs. We demonstrated the feasibility of this process during this effort. (See Appendix B). Data should be collected for a cross section of ship types, AN configurations, environmental conditions, and harbors. This effort would include riding and documenting performance aboard 20 to 30 ships in harbor areas. Ship's position would be accurately recorded on autotape systems. At least five trips should be made in the St. Mary's River for evaluating mini LORAN-C as an accurate short-range RA.

#### **6.2.4 Task 2.4. Conduct Preliminary Investigation of AN and RA Requirements**

Following initial at-sea and simulator data collection, a preliminary investigation will be made to determine how to best establish AN and RA requirements. The ultimate product of this effort in Phase III will be documentation of minimum requirements to be distributed to district offices. These requirements will provide guidelines for evaluating AN placement and configuration on a practical basis to obtain an acceptable level of safety.

Investigation of AN and RA requirements will be partly pragmatic, partly theoretical. At-sea data and workshops held with district office personnel will define the practical requirements and concerns of the navigator and the district office. AN performance models will be used to test the sensitivity of the measures of effectiveness to stated requirements. The output of this task will be identification and possible ranking of AN and RA requirements. However, minimum requirements will not be quantified in Phase II.

#### **6.2.5 Task 2.5. Conduct At-Sea Evaluation of a Selected Harbor**

In Phase II, it will be possible to determine the baseline performance of ANs in an existing harbor. Phases III and IV will project improvements for the harbor, change the ANs, and document that performance actually improved. Data can be collected aboard ships in the harbor, in part, during Task 2.3. Additional data collection in this task will be the documentation and quantification of traffic movement in the harbor year round. Ideally, a harbor will be selected where changes to ANs will improve both safety and traffic capacity.

### 6.3. PHASE III: ESTABLISHMENT OF AN AND RA REQUIREMENTS AND HARBOR EVALUATION

The practical application of the AN performance models will commence during the proposed Phase III effort. Three basic tasks will be completed. The AN performance models will be established on computer facilities at Coast Guard Headquarters; minimum AN and RA requirements will be established for transmittal to Coast Guard district offices; and improved AN configurations will be selected for the subject harbor. A fourth task in this phase is the evaluation of AN improvements for the selected harbor at CAORF.

Work will be conducted in four task areas. These follow.

#### 6.3.1. Task 3.1. Establish AN Performance Models at Coast Guard Headquarters

The main effort in this task will be to establish the AN performance models on computer facilities accessible to Coast Guard Headquarters. Instruction booklets and preprogrammed input matrices will allow evaluation of ANs and RAs in coastal and pilot waters, harbor approaches, harbor waters, channels, and rivers. Workshops and demonstrations will be conducted for branches within the Coast Guard (such as Short-Range ANs, Long-Range RAs, R&D, Ports and Waterways, and Engineering) who may have an interest in operating the model.

#### 6.3.2. Task 3.2. Establish Minimum AN and RA Requirements

The AN performance model will be used to test the sensitivity of AN design and placement variables in an effort to quantify minimum requirements as a function of type of AN or RA used, vessel types using AN or RA, and maneuvering room available for the vessel. The purpose of this effort is to compile a handbook of recommended minimum requirements. This handbook would ultimately be issued to district offices for use with the AN performance models that will ultimately be made accessible to them.

#### 6.3.3. Task 3.3. Evaluate Harbor with AN Performance Model and Project Improvements

The baseline performance data of the subject harbor will be reviewed and evaluated in this task. A set of AN changes will be determined to potentially improve safety or traffic capacity in the harbor. The AN performance models will be used to evaluate and select an optimum approach from candidate solutions. Special efforts will be made to ensure that the harbor's pilots and Coast Guard district officers are a vital part of the tradeoff process. Successful implementation of changes will depend on the support of these two groups.

#### 6.3.4. Task 3.4. Verify Improvements to Selected Harbor on CAORF

The AN improvements selected in the task above will be evaluated on CAORF. Particular emphasis will be placed not only on determining the effective improvement in safety, but also in assessing the potential risk caused by changing present AN configurations. Stat pilots licensed for the harbor, federal pilots, and other major users (i.e., tug and tow operators) will be used as subjects. If required, a training or re-orientation program can be investigated similar in context to the Valdez training presently conducted at COARF.

#### 6.4. PHASE IV: ESTABLISHMENT OF AN PERFORMANCE MODELS AT DISTRICT LEVEL AND VALIDATION OF HARBOR IMPROVEMENTS

During the 12-month Phase IV effort, AN performance models will be established at various district offices. Additionally, performance of new AN configurations in the subject harbor will be documented and verified to be as projected by the models. Harbor evaluation data will be used to update the AN performance model as required. Work will be conducted in three task areas.

##### 6.4.1. Task 4.1. Update Model and Use Techniques Required

The evaluation of AN improvements on CAORF and in the actual harbor (after changing ANs) will provide further insight into the use of the AN performance model to improve AN configurations. At completion of harbor re-evaluation, guidelines will be established as recommendations for model use. Modifications to subroutines will be made as indicated by the data.

##### 6.4.2. Task 4.2. Change AN and Verify Improvements in Harbor

AN configurations in the selected harbor will be changed according to findings from the model and CAORF harbor evaluation. Navigating performance will be initially evaluated immediately following the changes and again 6 to 9 months later to assess the short-term and long-term impact of changing ANs.

##### 6.4.3. Task 4.3. Establish AN Performance Models at Coast Guard District Offices

The final task of the AN performance modeling program will be to establish use of the models at the district level. This may involve use of desktop minicomputer technology, computer terminals, or installation or use of on-site computer systems. Establishing these systems at an operational level includes handbooks, recommended operating procedures, and demonstrations. Model operation and interpretation of results will be keyed to the minimum AN and RA requirements handbook developed in Phase III. Application of the system to real problems at the district level will be demonstrated in this task.

#### 6.5 USCG WORKSHOPS

Successful deployment of the AN performance model depends on close cooperation and input from the models' users in the Coast Guard, AN end users, pilots, and the marine industry. Therefore, a series of workshop/seminars are scheduled every 6 months starting at the beginning of Phase II. Initial meetings will be devoted to obtaining feedback from the Coast Guard on potential application problems for the model. The opportunity exists at the beginning of Phase II to redirect model development in those areas not yet finalized. Input and output routines are easily changed at any point in time to suit particular users.

Integrated participation of the Coast Guard and the marine industry is important to the analysis of AN and RA requirements. Basic concurrence on the capabilities of the Coast Guard as supplier of the aids and on the needs of the marine industry as user of the aids is needed.

As work proceeds into Phases III and IV, the nature of the meetings will change. Certain sessions may be related solely to evaluating and changing the selected harbor; other sessions may be related to the use of the models at the district office level.

Efficient conduct of these workshops, precise definition of the goals of the sessions, and careful selection of participants will ensure that the required guidance is provided for AN performance model development.

#### 6.6 RISK ASSOCIATED WITH CONDUCTING PHASE II, III, AND IV WORK

The risk associated with completing model development and validating the model in Phases II, III, and IV is extremely low. Extensive progress in model development made during Phase I ensures rapid completion of the AN performance model. Our existing modeling and marine human factors expertise will be directly applied to development of the AN performance models. The success of the models in generating reliable measures of effectiveness is equally well assured, because the models have already demonstrated their sensitivity to AN design changes and have been validated against preliminary data from CAORF and at sea. (See Section 5.) The sensitivity of the measures of effectiveness to AN configuration was demonstrated on the at-sea and CAORF data (Section 3).

The risk associated with collecting AN performance data both at sea and on CAORF is equally low. Our at-sea data collection trips in Narragansett Bay, Delaware Bay, and the Delaware River demonstrated without doubt that it is possible to evaluate AN performance while at sea. The use of more accurate ship positioning techniques such as autotape track recorders will serve to further enhance these data. Data collection at CAORF appears equally successful from preliminary results released by the Coast Guard. The dynamic runs through various AN configurations appear to vary significantly as a function of AN placement. Additionally, the ability to place a large number of pilots statically in the same place in a channel provides a unique opportunity to measure the statistical variations in visual perception position fixing. Pursuit of both at-sea and CAORF data collection efforts is urged above all other tasks. These data alone will provide quantified measurements of AN performance, presently lacking in the world literature.

Successful establishment of the AN performance models for use at Coast Guard Headquarters and district offices is equally assured. Navy tactical models, on which the AN performance models were patterned, have been used by the Navy for over 10 years. The syntax translator feature of the Navy models and the ability to change the model's program through decision and action statements have proven in the Navy to be the keys to the viability of the models in the long run. Operators of these models were able to run even the most complex problems after only two days' training. Simpler problems can be run with virtually no training through interrogation of input format on interactive displays. If it is decided not to issue the main navigating and steering model to the district offices, smaller versions of the fix and traffic models can be programmed in easy-to-use desk top computers. This was demonstrated during the Phase I effort.

# APPENDIX A TECHNICAL DESCRIPTION OF MODELS

## CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
A.1	INTRODUCTION AND OVERVIEW OF APPENDIX A	A-3
	A.1.1 Navigating and Steering Program	A-3
	A.1.2 Fix Model	A-3
	A.1.3 Static Piloting Model	A-3
	A.1.4 Dynamic Piloting Model	A-3
	A.1.5 Overview of the Scope of Appendix A	A-4
A.2	MODELING CONSIDERATIONS	A-4
	A.2.1 Utility Measures	A-4
	A.2.2 The Navigation Problem	A-5
	A.2.3 General Approach	A-5
	A.2.4 Special Considerations	A-6
A.3	MODEL TYPE SELECTION	A-7
	A.3.1 Description of Types	A-7
	A.3.2 Selection of Model Types	A-9
	A.3.3 Model Type Summary	A-14
A.4	MODEL STRUCTURE	A-14
A.5	FIX TECHNIQUES	A-17
	A.5.1 Prior and Posterior Probabilities	A-17
	A.5.2 The Grid Method -- Background	A-19
	A.5.3 The Grid Method -- Description	A-21
	A.5.4 Fix Objectives	A-27
	A.5.5 Information in Grid -- The Various Models	A-30
	A.5.6 Estimates of Position	A-31
	A.5.7 Fix Technique Summary	A-34
A.6	DECISION/ACTION LANGUAGE	A-35
	A.6.1 Introduction	A-35
	A.6.2 Decisions	A-35
	A.6.3 Actions	A-41
A.7	NAVIGATING AND STEERING MODEL -- FUNCTIONAL FLOW AND DESCRIPTIVE EXPLANATION	A-47
	A.7.1 Introduction	A-47
	A.7.2 List of Functions in Chronological Order as They Appear in the Navigating and Steering Model	A-51



(CONTENTS (CONTINUED))

<u>Section</u>	<u>Title</u>	<u>Page</u>
A.7.3	Input Function	A-52
A.7.4	Run Initialization Function	A-54
A.7.5	Case Initialization Function	A-54
A.7.6	Dead Reckoning Function	A-54
A.7.7	Retention Subfunction	A-55
A.7.8	Detection Function	A-56
A.7.9	Observation Subfunction	A-56
A.7.10	Perseverance Subfunction	A-57
A.7.11	Alignment Subfunction	A-58
A.7.12	State Estimation (Fix) Function	A-58
A.7.13	Electronic Fixing Subfunction	A-59
A.7.14	Fix Location from Observations Subfunction	A-59
A.7.15	Fix Confidence Subfunction	A-60
A.7.16	Wind and Current Estimate Subfunction	A-61
A.7.17	Decision Function	A-61
A.7.18	Action Function	A-62
A.7.19	Helmsman/Controller Function	A-63
A.7.20	Update Time Function	A-63
A.7.21	Update Position (Ship Dynamics) Function	A-66
A.7.22	Instrument Readings Function	A-68
A.7.23	Output Composite Statistics Function	A-69
A.8	GENERAL PROGRAM SUMMARY COMPUTER REQUIREMENTS, AND SIZE OF THE PRESENT DEMONSTRATION PROGRAM	A-69
A.8.1	Navigating and Steering Program Computer Requirements	A-70

## Appendix A

### TECHNICAL DESCRIPTION OF MODELS

#### A.1 INTRODUCTION AND OVERVIEW OF APPENDIX A

This appendix describes the models developed to examine the utility of aids to navigation (ANs) as these impact marine transportation. This investigation is focused on restricted waterways, alternate AN types, and AN configurations aiding navigation within those waterways, the local environmental factors, the ship's pilot and his skills and policies, the ship's helmsman and the ship. During the course of this first phase of the AN program, one model has been developed which accommodates all these major elements of the marine system. In addition, three related, supporting models were developed in order to gain insight into the relative qualities of AN configurations without including pilot decision-making in the process. The following paragraphs summarize these end products.

##### A.1.1 Navigating and Steering Program

This is the major output of the modeling effort. The navigating and steering program is constructed to completely model a ship traversing the waterway in the presence of various ANs. It has sufficient flexibility to allow the analyst to create a model for the specific configurations and types of ANs, as well as other influential factors such as piloting policy, ship type, helmsman response, and the human decision-making process. This model is created by appropriate input English language phrases to the supplied program. The navigating and steering program is of the Monte Carlo type. Multiple traverses of the waterway are simulated and the statistics of such important measures as ship track distribution can be obtained through appropriate commands to the program.

##### A.1.2 Fix Model

The objective of the fix model is to determine the tightness of fix available from ANs. The variance in each direction of the product of the a priori distribution of observations represents the amount of information available to the pilot.

##### A.1.3 Static Piloting Model

The objective of the static piloting model is to determine the distribution of fix confidence which would occur from a series of single observations of the AN configuration. The maximum a posteriori probability (MAP) estimate indicates observation bias error; variance around the MAP estimate provides a measure of pilot confidence in fix accuracy.

##### A.1.4 Dynamic Piloting Model

The objective of the dynamic piloting model is to determine the distribution of fix confidence which would occur from observation and dead reckoning while a ship follows a prescribed track. The results are the same as found by the static piloting model, except that the net bias and the net confidence include dead reckoning (DR) factors and observation perseverance.

### A.1.5 Overview of the Scope of Appendix A

The following sections include a discussion of modeling considerations (Section A.2), a review of modeling alternatives and type selection (Section A.3), and an introduction to the selected model structure (Section A.4). The remaining sections expand upon component parts of the basic model. Section A.5 explains in detail the characteristics and assumptions of our fix estimation techniques. This section has been written for both the individual not recently familiar with statistical modeling and those who are more current in the field. Our bridging of this gap will require some patience on the part of the reader. Section A.6 describes the characteristics of the language created especially for this application. The process for inputting pilot decisions, characteristics of the navigation of specific channels, AN configurations, etc in an English-like language is presented at a functional level. Section A.7 presents a functional flow and information of the navigating and steering model for the reader interested in a more detailed review. Section A.8 summarizes the model process and describes the size of the present demonstration computer program and its computer requirements, and then projects the final program's size and characteristics.

The reader should also be aware that several of the salient points contained in this appendix have been presented in the main body of the report. This appendix represents complete presentation of the model as presently developed and the underlying rationale.

The structure of the navigating and steering program is fully developed herein; however, the various submodels are in different stages of completion, although working models for each function exist within the demonstration computer program.

Detailed mathematical derivations have been omitted for clarity in presentation of the overall model concept. In accordance with this philosophy of macro-view, rather than micro-view, focus is placed on the reasons for and implementation of the unique features of this Monte Carlo model. These unique features are the procedure for determining fix from the observations of the aids to navigation, the flexible structure for implementing decision logic and action logic in the model using English language phrases, and the overall model adaptability in handling other types of navigation aids. The model structure as developed is not only useful for evaluating ANs and other navigation aids, but also is a valuable tool for evaluating the impact of piloting policy and requirements for additional pilot training to more safely and efficiently handle ships in a specific waterway.

## A.2 MODELING CONSIDERATIONS

### A.2.1 Utility Measures

The underlying requirement for this modeling effort which focuses on ANs is to provide a means for evaluating utility, value, or benefit measures for alternate AN configurations as they influence the performance of marine systems. Given this basic requirement, it is necessary to define the measure of utility, value, or benefit to be employed and the model then simply expands upon this basic measure. The selection of one or more measures of utility will be fundamental to the evaluation process. It is clear that the modeling process must generate the parameters which will be used in the selected evaluation measure. However, the modeling process does not need to await the final definition and approval of a utility function. Existing marine transportation systems can be modeled. The model must, however, be sensitive to those navigation issues and factors that bear on marine system performance.

Since utility measures (e.g., environmental impact versus profit motive impact) can differ as a matter of viewpoint and can change over time, the modeling effort is not keyed to any specific measures in this early phase of the effort. For this reason, a modeling policy has been selected which avoids keying to any preconceived measure, but rather is sensitive to parameters and factors known to influence marine system navigation and operation. These parameters will be identified and further defined as the description of the modeling development process proceeds.

#### A.2.2 The Navigation Problem

Approximately 70 percent of all marine casualties for large seagoing ships take place in harbors and harbor entrances. An additional 20 percent occur in coastal zones on a world-wide basis. These are the areas served by various navigation aids located to assist mariners in efficiently and safely bringing the ship to the desired port. The heavy congestion and small error tolerances in harbor regions require the use of experienced licensed pilots.

The United States Coast Guard problem in these areas has many facets. As a public servant, the Coast Guard is sympathetic to requirements for harbor efficiency and assists in improvement of cargo flow to the extent that such improvement is not in conflict with its principal responsibility of ship safety. Navigation accuracy is influenced by location and types of ANs placed in the waterway, the landmass surrounding the waterway and its usefulness in the navigation process, and the incorporation of newer technology in radio aids, transmitter locations, and receiver requirements on ships using the waterway. Ship safety is influenced by both navigation accuracy and piloting policy. It is clear that there is a tradeoff or interaction between the character of an AN configuration and piloting policy. A high information content, high quality AN configuration may provide marginal value if it is not matched by appropriate adjustments in piloting policy/practice. Conversely, modifications in piloting policy could yield high value from lower information content, lower quality AN configurations. In the development of a marine system model that highlights AN impact, both measurement of the quality of information available from an AN system and the pilot's behavior in response to the AN system configuration must be considered.

#### A.2.3 General Approach

The dictionary supplies two definitions for the word model which apply in the current context: (1) "a description or analogy used to help visualize something that cannot be directly observed"; and (2) "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs".

Most elements of a model for navigation performance are not directly observable; only the results of these procedures are observable. For example, a pilot can be asked to indicate where he thinks he is located, but not to describe the process by which he combined the observed positions of the visible ANs with what he remembers to obtain this location.

The process for designing a model for navigation performance becomes a multiple step procedure:

a. Decide what to emulate with the model. In this case, the overall path of a ship of specific handling characteristics with a human pilot and helmsman in navigating a prescribed waterway was selected (the second definition of "model").

b. Determine the major functions that must be simulated to create this model. In this case, dead reckoning, detection, fix, decision, action, helmsman, and ship position update were considered necessary functions to obtaining the pilot and ship response to the available ANs.

c. Model each of these major functions. It is at this level that knowledge of the human thought process is combined with the questions which need to be solved to determine the pattern (structure) of the functional submodels.

d. Combine these submodels and tune the combined algorithm by at-sea and CAORF data to create a model which closely replicates the actual observed data.

A model that stops here does not have great utility. All that has been demonstrated is the capability to duplicate already known performance. The value of a model is extrapolation or transference to other problems. This is why the human decision making process is behind the algorithms which involve decision, and actual ship dynamics equations are behind the algorithm which creates ship response to helmsman orders. Experience has shown that when a model is built around the processes as they actually occur at sea and the coefficients determined by in-situ measurements, the greatest probability of valid results is obtained for extrapolated conditions.

#### A.2.4 Special Considerations

All too often a modeler, in a drive to display his modeling competence, displays insufficient sensitivity to the process which he has been charged with modeling. Given this tendency, one or more segments of the process are singled out which appear to be significant, tangible, and manageable from an analytical viewpoint. Such subanalysis can give preliminary insights; however, the apparent analytical manageability is often based on assumed process behavior. There is a substantial graveyard for such models which died when these assumptions failed to meet the test in the actual process. The marine system navigation process offers just such temptation. The information quality offered by a particular AN configuration tempts the analyst because it meets his criteria, including manageability. The fact is, human participation in the process is unpleasant from the modeler's viewpoint. Some of the modeling complications of human participation in the navigation process are discussed in the following paragraphs.

The human being is characterized by discrete decision and actions. A servo-controlled feedback rudder controller may give orders in fractional degrees and utilize a smooth algorithm to actually attain the ordered heading, but a real helmsman will steer the rudder in three or four discrete steps with finite step changes.

The actual navigation procedure is performed in a serial fashion. A single observation of an AN is made. This observation is combined with previous information to give a new fix. Based on this new fix, a decision is made as to whether the ship steering should be corrected. The appropriate order is given. The helmsman responds to the heading order by giving a pattern of rudder orders based on previous experience and the heading and speed information available. The ship responds to the rudder orders according to its own characteristics. Each of these processes depends on the previous and takes time.

The human demonstrates perseverance. This is the tendency to stick to a previous decision even when current data indicates a new decision is required. This is a key process which can be overridden at critical decision points through sufficiently strong redundant information externally supplied. Perseverance is directly related to AN information requirements at turns and near dangerous shoals, etc.

The human process is non-Gaussian. Detection probability is more closely described by a power process (Rayleigh distribution). Estimated range has a Gaussian distribution in angle subtended to the eye, which results in an extremely skewed probability density in range. These are just some examples of the non-Gaussian processes which occur throughout the model.

Finally, the human relies on stored information. Previous knowledge both accumulates confidence in the decision which is made and provides a foundation for distrust of current observations if not consistent. The dynamic interaction between forgetting (or incorrectly remembering) previous information and using this previous information to influence the confidence in current observations is a fundamental part of the model.

The navigation process is characterized by some events which take place on a time schedule, and other events which take place on a conditional basis. The model should be constructed on a variable time basis to permit entry into the appropriate submodel whenever required and to skip submodels when their functions are not required. Examples of variably timed events include frequency of fix, ship control functions, and decision/action logic.

In summary, this modeling effort will seek to support a wide variety of utility measures; it will be organized to investigate the interaction between piloting practice and AN quality; and it will avoid early commitment to assumptions which may be analytically expedient on one hand, but risk failure to validate on the other.

### A.3 MODEL TYPE SELECTION

Three major types of mathematical models could have been selected for this application: Mean Value, Probabilistic, and Monte Carlo. Each has distinct characteristics; selection of model type must consider these characteristics in the light of the problem being solved. The navigating and steering model for detailed evaluation of navigation performance is of the Monte Carlo type; the fix and piloting accuracy models are of the probabilistic type. This section examines the reasons behind these selections.

#### A.3.1 Description of Types

The major characteristics of each of the model types will be described, emphasizing features which directly relate to their utility in solving the navigation performance problem.

a. Mean Value. The mean value model type has fast running speed as its major advantage. For very large problems which require many variations, it may be the most economical way of determining sensitivity to the individual independent parameters. In this type, each parameter is characterized by a single number, the same number each time the model is run. This selected number, in most cases, is the mean of the distribution of values which would realistically occur, although other single numbers such as largest mode or median may sometimes be selected where they seem more appropriate. Sensitivity analysis is performed by varying each parameter individually and observing the impact of this variation on the final result.

Substantial problems exist in using the mean value model type for the navigation performance analysis. Other operations besides addition (and subtraction) take place

within the model. Even though the mean of the sum of two random variables equals the sum of the means of each variable, the mean of the product is not the product of the means if the variables are not completely independent. Therefore, some of the calculations performed in the model could give the wrong answer. The human behavior of the pilot and helmsman is not based on the mean result, but on the specific value currently being observed. The resultant decisions are discrete in character. Therefore, certain specific combinations of observations and actions which may, in real life, result in the ship running aground can never be observed out of a mean value model. This is a direct result of the fact that these functions are actually performed in a serial fashion. The results of one function are the direct inputs to the next.

b. Probabilistic. The probabilistic model type is somewhat slower running than the mean value type; however, in analytic forms it produces answers considerably faster than the Monte Carlo type. In this type of model, the output of each function is a probability field. This output is the conditional probability of output y occurring given that x was input, multiplied by the probability that x actually was the initial condition, and summing the results over all possible input values. That is, the output of each function is characterized by the probability that each specific combination of possible input conditions occurs. The probabilistic type model does satisfy the objections raised for the mean value type of model. The resulting probability space from each function is a correct combination of the input probabilities; and thus, possible cases where drastic results could occur are predicted.

However, the major advantage of faster running time than the Monte Carlo type of model disappears when the probabilities must be handled as discrete multidimensional spaces (the exhaustive approach) rather than continuous analytic functions. This technique is required for the navigating and steering model because the human pilot and helmsman make discrete decisions based on probabilities which are not Gaussian in output parameter space.

The probabilistic type model is not easily related to the physical parameters of the system it models. Incorporating input changes may require extensive probabilistic calculations to determine how to modify the model. Many of the operations which are performed are serial; that is, dependent on the previous output. Therefore, the probabilities are not independent and the impact of correlation must continually be assessed. Finally, since many functions have multiple output variables, the probability space describing the output of that function must cover every possible combination of these outputs, a process requiring a great deal of computer time and memory. Approximations are possible to reduce the impact of one or more of these problems; however, the approximations must be chosen so as not to materially influence the final result.

c. Monte Carlo. The Monte Carlo model is conceived on the principle of accumulating statistics of actual events. To find out how often ships do not successfully negotiate a specific turn in a channel, the analyst will look at the tracks for a large number of ships and determine what fraction of them were not successful. The Monte Carlo model mathematically uses the same direct technique. Each function which actually occurs is individually modeled and these function models are combined in a computer program which simulates one ship on one pass through the channel. In this sense it is the same as collective data at sea on one passage through a channel as we have available in our at-sea data bases. Many such passes are simulated and the accumulated statistics are determined. The principal advantages of the Monte Carlo model type are flexibility, capability of handling both dependent and independent operations, and ease in verification and tuning to empirical data.

The principal disadvantage of the Monte Carlo model is running time on the computer. The running time problem is not nearly as significant today as it was several years ago. Computers are faster, less expensive, and physically smaller. Desktop minicomputers can rapidly handle problems which were a grind for the monsters of several years ago.

The Monte Carlo model is the slowest of the model types examined, but it also is the most direct. The number of assumptions are minimized because the individual functional blocks duplicate the actual processes which occur down to specific rudder orders and ship response.

d. Summary of Model Types. TABLE A-1 compares some of the major features of each model type described above. Each type of model has applications to which it is best suited and may incorporate submodels of a different type internal to the overall model. For example, the simplest detection model for visual observation of an aid to navigation is of the definite range law or "cookie cutter" type. In this model, if the range to the AN is smaller than the visible range and it is simultaneously less than the horizon range, the AN is detected. This is a mean value type of model. A more complex (and more realistic) detection model calculates the probability of detection for the single AN at that range in the prescribed visibility, the probabilistic model type. To use this in a Monte Carlo type model, a "properly weighted coin is tossed" (a random number selected out of the distribution) and the detection yes-no question is answered for this pass through the channel at this time.

#### A.3.2 Selection of Model Types

It was decided that the overall model for navigation performance required the capabilities inherent in the Monte Carlo type, but that the submodels which perform each function within the model could be of more efficient construction. A more detailed explanation of the reasons behind the decisions follows.

a. Navigating and Steering Model. The principal requirement for the model is that it measures the performance of ships in the presence of different configurations of external ANs and other navigation aids carried by the ship. In support of this requirement, it was determined that human perception of the situation plays a key role and the piloting policies (decisions and actions) are dependent on the perceived situations. Although any of the model types, when properly designed, could be used in this role, the direct approach of the Monte Carlo type has the greatest appeal for reasons of:

1. flexibility,
2. empirical data matching capability,
3. minimal programmer support in use, and
4. handling non-Gaussian distributions.

The disadvantage of slow running time is overcome in two ways. First, modern computers are getting faster. Second, a navigation information (fix accuracy) model is also being supplied which can be used to pre-select candidate AN configurations. This filtering process has been found to be a valuable asset in reducing the number of configurations which are to be analyzed in detail without sacrificing the detailed analysis.

As an example, suppose that four possible configurations were being examined ( $\alpha$   $\beta$   $\gamma$   $\delta$ ). Implementation and maintenance costs were such that  $\alpha$  was the least expensive, followed by  $\beta$  and  $\gamma$ , with  $\delta$  as the most expensive. Running the fix



**TABLE A-1. MODEL TYPES COMPARISON**

Type	Flexibility to Input Changes	Computer Running Time	Dependent Process	Ability to Handle		Empirical Data	Computer Programmer Support Requirement
				Realistic Distributions	Discrete Events		
Mean Value	Good	Fastest	None	None	Good	Poor	None
Probabilistic (Analytic)	Poor	Fast	Limited	None	Poor	Poor	None
Probabilistic (Exhaustive)	Poor	Slow	Good	Good	Good	Fair	Considerable
Monte Carlo	Excellent	Slowest	Good	Good	Good	Good	Little

accuracy model first may find that  $\delta$  was the most accurate,  $\beta$  was next, followed by  $\gamma$  and  $\alpha$ . Therefore, there is no need to provide detailed analysis on configuration  $\gamma$ , since it is more expensive and provides less information than  $\beta$ . In addition, if it is determined that the fix accuracies supplied by  $\beta$  and  $\delta$  are both better than the pilot can realistically use, it would not be necessary to analyze  $\delta$ . Therefore, in this example, only configurations  $\alpha$  and  $\beta$  need to be analyzed in detail. TABLE A-2 demonstrates this example case.

b. Detection Submodel. There are two model types internal to the detection submodels. A mean value model is used when definite range law detection is postulated. A probabilistic model type is used for the more general case. The selection of the appropriate model is a user choice prior to performing the analysis. The criteria which are to be used are summarized below:

(1) Definite Range Law Detections. The principal advantage of this model is efficiency in running. In cases where the visibility is greater than the horizon range, the definite range law algorithm applied to the horizon range is appropriate. When there are a large number of ANs within the horizon range, the definite range law algorithm can be applied with a shorter detection range because the fix information contributed by the close aboard ANs dominates the total fix. If the user is not sure whether either of the above cases applies, the more general probabilistic detection submodel can be used with a small increase in running time.

The definite range law detection submodel (also called "cookie cutter" detections) tests for detections (yes or no) based on a comparison of the actual range to the AN and the detection range. If the actual range is less than both the detection range and the horizon range, the algorithm specifies that a detection has taken place (yes). Otherwise, a detection has not occurred (no).

(2) Probabilistic Detections. The probabilistic detection submodel is the more general detection model. Its use is recommended whenever a clear-cut decision to use the definite range law detection model does not exist. The use of the probabilistic model is extremely important in cases of limited visibility (fog, rain, etc) where only a small number of ANs may be visible at any one instant (including none visible at some points).

In the probabilistic model, the intensity of the source (e.g., the light on a lighted aid), the background level, the reflectivity for daytime non-lighted aids, the absorption and spreading losses from the aid to the ship, and the resolution capability of the detector (e.g., the eye for unaided visual detections) are combined to obtain the mean signal-to-noise ratio excess above detection threshold. The logarithm of this excess is the median of a log-Rayleigh detection distribution. A single sample is taken from the detection distribution. If this sample is negative, a detection has not taken place. Otherwise, the aid is detected. There is also a hysteresis effect (alertment factor) which reduces the probability of losing contact on the AN once a detection has been made.

The principal output of the detection model is just a "yes" or "no" answer to the question as to whether a detection has occurred in the current time step on each of the ANs in the channel.

c. Fix Submodel. The fix submodel is separately described in Section A.3 of this Appendix. In general terms, it is of the probabilistic type where the resulting probability space is the pilot confidence that each point is the actual ship location. The maximum likelihood estimate of ship location is the point of highest pilot confidence. The

TABLE A-2. EXAMPLE OF AN CONFIGURATION CANDIDATE SELECTIONS

Configuration	Total Cost	Fix Accuracy	Decision	Usable Fix Accuracy	Decision	Detailed Analysis
$\alpha$	Least	Least		Least		X
$\beta$	Low	High		Maximum		X
$\gamma$	High	Low	Eliminate ( $\beta$ is better)			
$\delta$	Most	Most		Maximum	Eliminate ( $\beta$ is better)	

subsequent decisions and actions which the pilot makes are based on his estimated ship location and on how confident he is in that estimate.

d. Fix Accuracy Model. The fix accuracy model is the "back of the envelope" calculation procedure for examining which configurations of aids to navigation should be investigated in detail and which offer no benefit over configurations already being examined. This model contains a definite range law detection submodel, the fix submodel, and dead reckoning between fixes according to the dead reckoning submodel (to be described later). The fix accuracy model is of the probabilistic type construction and has two operating modes: static and dynamic. The static outputs are the fix probability space in terms of information supplied by the aids and the standard deviation of fixes which would occur due to actual observation of the aids. The dynamic mode uses the dead reckoning algorithm, assumes the ship exactly follows a specified track, and that all observations are error free. Its output is the pilot's confidence in fix based on both the current fix and the dead reckoning information. Both of these models are constructed to address the question of how much information is available from the AN configuration; they do not address the second part of the question which is what happens to the ship track as a result of this information.

e. Decisions/Actions/Helmsman. These are the human elements of the navigation performance model. They are input through the language syntax translator to the navigating/steering program to create the model. This process is described in Section A.6, which covers the decision/action language.

These functions contain a mix of the mean value type model and the probabilistic type model. Given the outputs from the fix and the knowledge of the harbor, the pilot makes decisions as to whether corrective orders are needed based on comparison to either a pre-specified parameter threshold value or a number drawn from a specified decision probability distribution. He then takes actions by giving the appropriate orders, if required. The helmsman steers the ship based on the pilot orders, his steering equipment readings, and visual references which are again drawing from the appropriate probability distribution.

f. Dead Reckoning. The dead reckoning submodel is probabilistic in construction; however, the algorithm for creating the probabilistics is dependent on human (pilot) decision making and is controlled by the decision/action commands. The algorithm starts with the pilot confidence space which comes from the fix model. Taking each of the points where the ship could actually be located, the result of dead reckoning that point is calculated allowing for pilot confidence in course and ground speed (which are derived from heading, water speed, and the perceived effects of wind and current). This is multiplied by the pilot's confidence that each point was where the ship actually was located, and summed together. The result is a probability space which describes the pilot's confidence of being at each location in that space after dead reckoning is performed. This probability space is the initial condition upon which the new fix will be mapped.

The decision and action commands affect this algorithm in the following fashion. A pilot who is flexible and allows all available information to affect his decisions uses the algorithms as described. Another pilot who makes a firm decision that "this is where I am" following a fix will modify his confidence space to specify that single point. Then the DR algorithm (used as described above) is a mapping of this single point through the speed and course confidence into a much more tightly clustered probability space upon which he builds his fix. Most pilots will behave between these extremes; thus, a weighted algorithm combining these procedures is required. The actual way in which the confidence space following fix is modified is directly controlled by the appropriate action command.

### A.3.3 Model Type Summary

Most of the individual submodels which are part of the navigating and steering model are probabilistic in construction. This reflects the fact that the human operator makes the observations and then applies judgment to determine what these observations tell him. Thus, the selection of the perceived fix point reflects the application of judgment. Then, the pilot behaves in a serial fashion, making discrete decisions and taking specific actions based on the present situation. Using this perceived fix, he decides whether a change in ship heading or speed is required and orders the required change. As the ship is responding to the helmsman's orders (in response to the pilot's orders), the pilot continues to make observations from this new ship position and apply further corrective orders.

In examining this process, it was considered necessary to create a model which duplicated the single ship track, allowing for the discrete commands which actually occur as a result of the ship location, turning rate, and channel characteristics. It was not felt that a probabilistic model could be constructed which adequately handles the impact of the human being in the overall navigation process. The Monte Carlo type construction selected for the model reflects the impact of policy (decision making) in a direct way because the ship is taken all the way up the channel. Then the model is reset to new initial conditions and the ship is taken all the way up the channel again. After multiple runs up the channel, statistics on ship navigation can be determined and the impact of the configuration of aids to navigation assessed. This approach is similar to collecting multiple data collections at sea under various conditions.

Flexibility is another advantage of the Monte Carlo type model. Different decision strategies can be examined, as well as the impact of weather and traffic, simply by changing input parameters. A probabilistic model is not flexible in this same way. For a probabilistic model, the probability that each result would occur from the decision strategy, traffic pattern, etc, would have to be analyzed and the results programmed by completely rewriting the model.

### A.4 MODEL STRUCTURE

The selected structure for the navigation performance model involves the creation of a program which governs the analysis (the navigating and steering program) and a language through which the model can be created by the user to simulate the specific problem to be examined. Flexibility and user orientation were key elements in the determination of this structure. It has already been mentioned that the selection of the Monte Carlo type governing program was made partly because its functions directly parallel actual operational functions. Therefore, the program has the potential for a high level of flexibility at the user level. It is the purpose of the selected structure to develop this potential. That is, the model structure was selected to give the user a way of easily saying, "This is what I want to do - duplicate it," to the computer.

There are two principal reasons why this type of user-centered flexibility was considered to be essential. First, due to the impact of piloting policy on the eventual ship track, different levels of pilot skills have to be handled. As a side benefit, the selected program/input language structure also has value in policy development and evaluation for pilot training applications. Second, every waterway is different. Different width, depth, traffic type and density, surrounding land mass, shoals, reefs, and other dangers characterize each waterway. The requirement for type and placement of ANs and the utility of electronic systems must be individually tailored to the waterway under investigation. The five test scenarios, discussed in Appendix B, were selected because

they are actual East Coast waterways from which data can be gathered for model verification. Also, the scenarios have radically different mixes of ANs and other navigation aids in addition to having different requirements for single transit navigation time and accuracy.

FIGURE A-1 shows the structure of the navigation performance model. Note the distinct character of the navigating and steering program in that it is not logically a complete model ready for data. The inputs include actions and decisions which complete the logic to make a model. The remainder of this section focuses on the model flexibility which is a direct result of this structure.

The decision and action modules model the pilot's thought processes and behavior. To allow the greatest operator-centered flexibility in this area, the human decisions are controlled by inputs in an English-like language. All the pre-programmed modules do is interpret the logic which the user has written. Thus, the user has complete control over the type of pilot he wants to model, in terms of the pilot's usage of equipment, confidence in sensors and fixes, maneuvering behavior, etc. He also has complete freedom to model any type of piloting philosophy he desires.

The English-like language is made up of a vocabulary of key words or phrases that the program recognizes, and a syntax or set of rules for combining these words into "sentences" that the program can understand. An example sentence would be:

IF TIME < 5 MINUTES, (THEN) SLOW TO 1/2

The logic translator interprets the input set of "sentences" which describe the pilot's logic and behavior, and changes them into the form appropriate to drive the decision and action modules in the program. Although the human logic may be just as easily programmed directly into the decision and action modules, the advantages to keeping the logic as an input can be summarized in the key words; flexibility and user comprehension. The English language sentence structure of the logic input allows the user to fully understand an entire set of commands and how they interact. This direct visualization would not be available if these commands were simply written in computer language. Once the user understands what is in the decision and action logic and the sentence structure, changes are easily made and directly feed the translator to become part of the model. This feature leads to almost unlimited flexibility.

The value of this framework type of program structure has been extensively proven in a tactical engagement program which has been delivered to the military. This program has demonstrated the unique capability of adapting to new systems and ideas to assess their impact and of being easily reconfigured when experimental results of at-sea exercises produce different results than previously expected. The navigating and steering program was constructed to have the same comprehensibility and adaptability by using refinements on the techniques incorporated into the military engagement model.

We have purposely referred to the navigating and steering program in this section, as opposed to the navigating and steering model. This is because the program was constructed as the open framework or surrounding structure for performing the Monte Carlo analysis. It contains some generalized logical modules (such as detection, dead reckoning, fix, and ship dynamics) and some empty slots into which logic is inserted (such as the decision and action modules). The input module interacts with the operator and the input library to provide all of the data needed to define the scenario and all of the logic needed to fill the empty slots. Thus, the "model" is the description of the specific scenario, and does not exist until the input and program are combined.

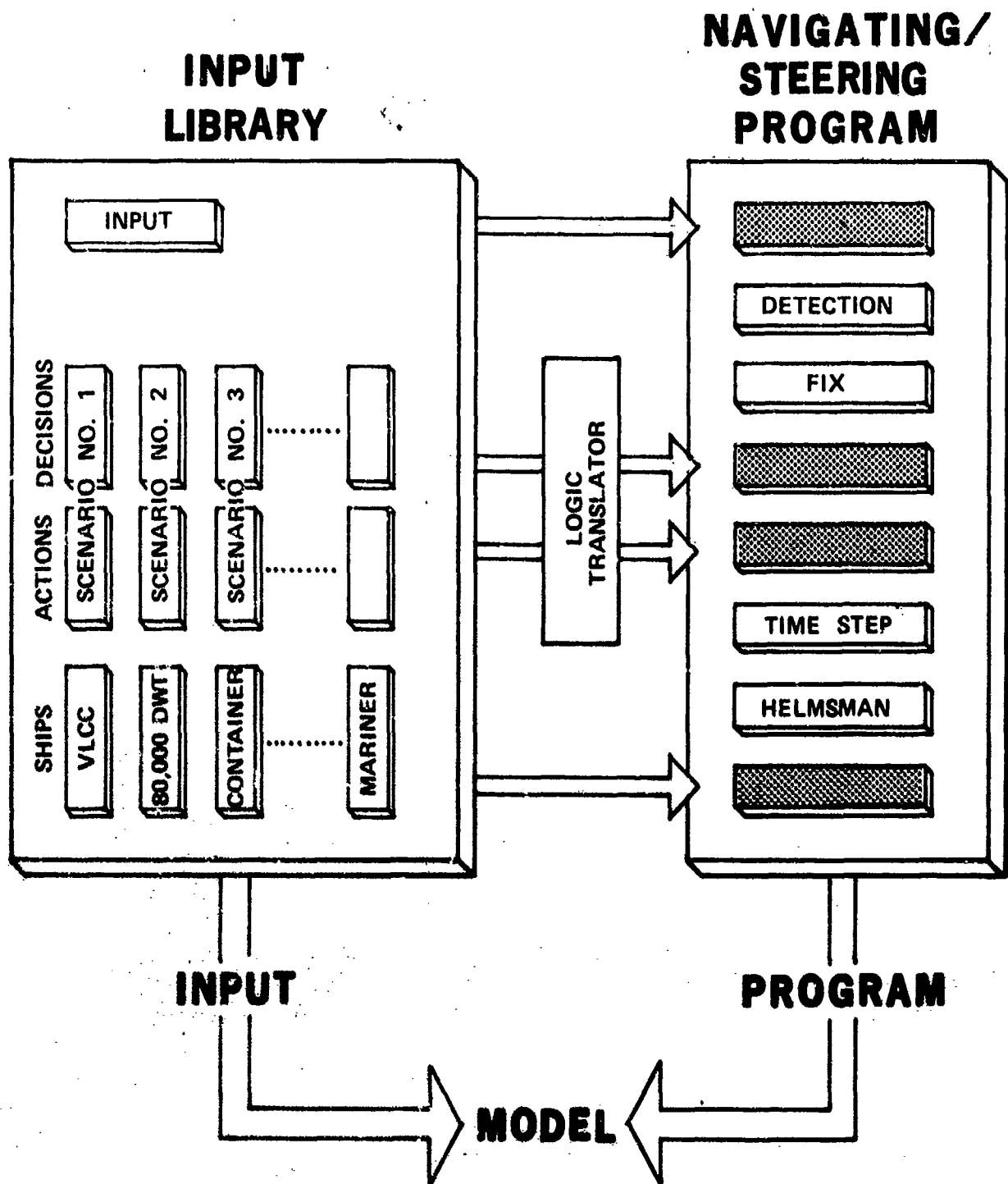


FIGURE A-1. SYNTHESIS OF MULTIPLE SCENARIOS

## A.5 FIX TECHNIQUES

The procedures by which the pilot estimates position by combining the observed bearings and ranges to each AN with the dead reckoning and electronic fix information is the core of the model. The pilot uses this positional estimate and his confidence in this estimate for making his steering decisions which set the path of the ship. In any one observation, the pilot may gain a bearing to one or more ANs of different types; he may or may not have an associated range estimate. Therefore, the fix technique was selected to handle the following conditions:

- a. Visual observation of a bearing to an aid;
- b. Multiple observations of bearings and/or bearings and ranges which may not be consistent in fix location;
- c. Shoals, submerged wrecks, etc, which would modify the risk the pilot takes if his positional estimate is incorrect; and
- d. Ship equipment and electronic aids (radio, radar, pelorus, etc).

As has been previously described, the fix model is of the probabilistic type. It uses DR information (from previous fixes and perceived course and speed), the present observations, and the cost of error to obtain a risk function according to a Bayes estimation algorithm. The position estimate on which the pilot acts is based on a minimum risk criterion.

### A.5.1 Prior and Posterior Probabilities

Two related but fundamentally different probabilities are used in the fix algorithm. The prior (a priori) probability is the probability that  $X_0$  is observed, given that  $X_A$  is the actual value for  $X$ . This is sometimes described as the parameter space from which the observation is taken. The posterior (a posteriori) probability is the probability that  $X_1$  was the actual value, given that  $X_0$  was observed. This is alternately described as the observation space from which the estimate is made. Even though, in many cases, both of these probabilities would be described by the same function (built around  $X_A$  for the a priori and  $X_0$  for the a posteriori cases), they are conceptually different.

For example, a simple bearing estimation algorithm would be constructed about a Gaussian distribution on observed bearing. In this case, the a priori and the a posteriori probability distributions would be identical, except that the a posteriori would be centered on the observed value and the a priori would be centered on the actual value for bearing.

As another example, the daytime visual range estimation algorithm which is included in the model is built about a Gaussian distribution in retinal angle subtended by the AN height. FIGURE A-2 shows the a priori distribution of estimated range for a pilot eye height of 45 feet and an AN which is 9 feet high at a range of 250 yards. The sigma on observed retinal angle is 10 minutes of arc. (These numbers are example values which will be dependent on the ship, the AN, and more detailed verification from the at-sea data base.) Mathematically, this distribution has its median at the actual value; i.e., 50 percent of the observations will be less than the actual value and 50 percent will be more. However, the skew of the probability density indicates that when a smaller than actual



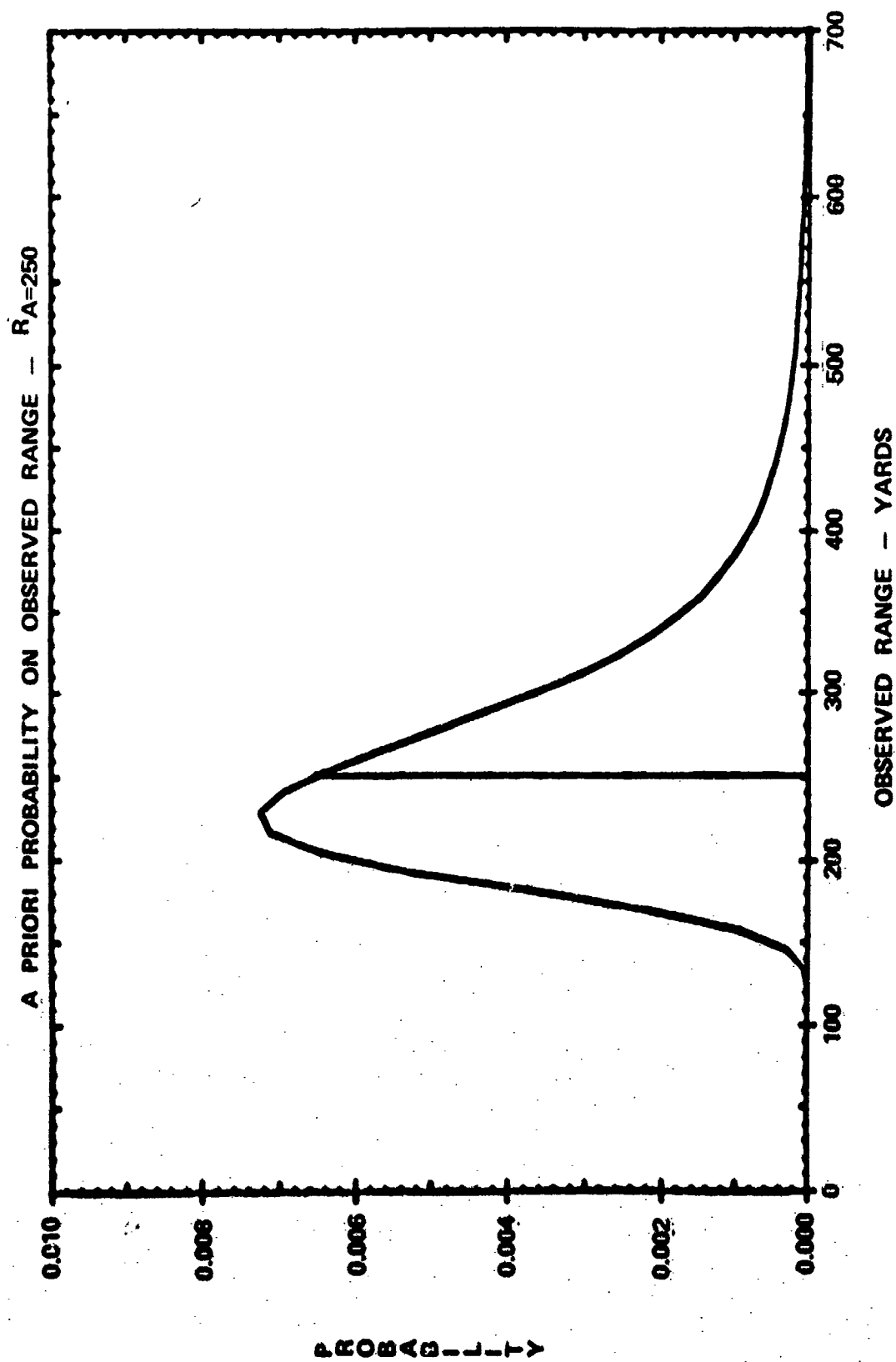


FIGURE A-2. A PRIORI PROBABILITY ON OBSERVED RANGE -  $R_A = 250$

range is observed it is likely to be fairly close to the actual range. When a larger than actual range is observed, it may be considerably farther away from the actual. The average of many observations of range taken from this distribution (the mean) is larger than the actual range (the mode). This confirms the tendency of an observer to overestimate the average range as indicated in the at-sea data.

In the model, a single value is selected from this distribution in each time step. When the observations are independent (perseverance is insignificant), this selected number is the observed range. The next step is to find the a posteriori probability. That is, given that  $R_o$  was the observed range, what is the probability that any specific range ( $R_i$ ) was the actual range ( $R_A$ ). The estimation criteria, which will be described later, are structured around this a posteriori probability density. The technique to calculate this probability is conceptually simple. A range  $R_i$  is assumed to have been the actual range, and the probability per unit range that  $R_o$  would have been observed is calculated. A different range  $R_j$  is then assumed and the associated probability of observing  $R_o$  is calculated. After calculating the probabilities over the entire possible set of range values, a normalization constant is determined which makes the area under the probability density curve equal one. The normalized probability density as a function of postulated actual range is the desired a posteriori function.

The a posteriori probability density for three possible values of observed range is shown in FIGURE A-3. The a priori probability density (described in FIGURE A-2) is also shown. Two important observations on the shape of the a posteriori probability can be made:

- a. The peak probability occurs at the observed range.
- b. The a priori and a posteriori probability densities have different shapes.

For this example, it has been verified that there is no specific observed range at which the two probability densities would be identical. The Bayes minimum risk criterion specifies that when the cost of an incorrect observation is independent of the magnitude of the error, the best estimate of the parameter is the Maximum A Posteriori Probability (MAP) value, which is the value of range where the peak probability occurs. Therefore, with a uniform cost function and only one observation, the estimated range will be the observed value. A more detailed explanation of the relationship between the MAP estimate, the Maximum Likelihood Estimate, and the Bayes minimum risk estimate will be given following the discussion of the procedure which is used to combine the data.

#### A.5.2 The Grid Method - Background

It was first determined that the fix model was to be of the probabilistic type, the output of which is the a posteriori probability that the ship is located at each specific position ( $X_i, Y_i$ ). Since it was considered necessary to have the capability of handling arbitrary shapes for the a posteriori probabilities without making predefined mathematical approximations, a closed-form approach was not selected. The selected grid method could be termed point-exhaustive, since it involves examining each possible value of  $X_i$  and  $Y_i$  and determining the a posteriori probability that the ship is actually located at any point

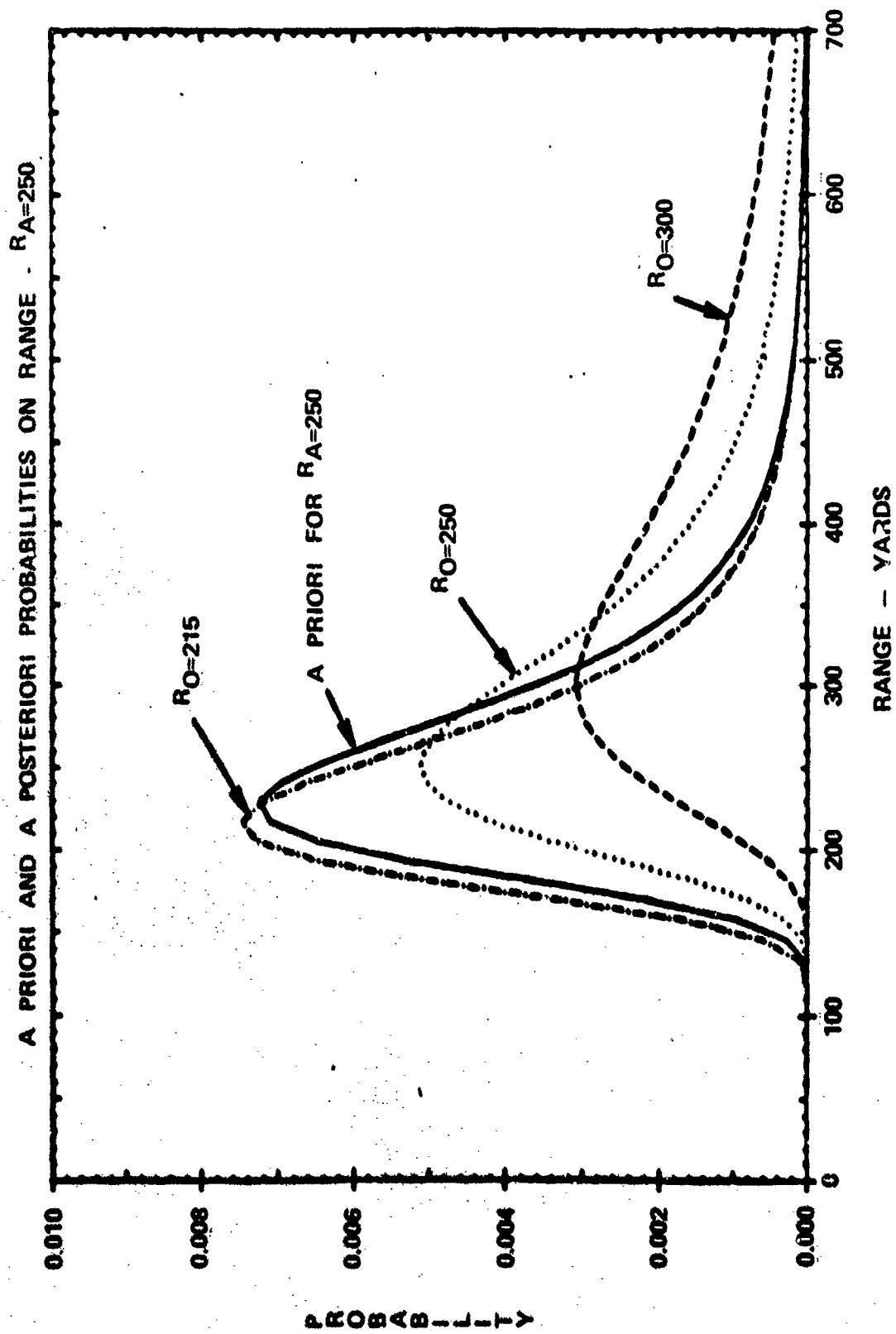


FIGURE A-3. A PRIORI AND A POSTERIORI PROBABILITIES ON RANGE -  $R_A = 250$

in a grid. An advantage of the point-exhaustive approach is that a realistic cost-of-error function can be mapped across the a posteriori probabilities to allow use of the Bayes minimum risk estimation approach. There are only certain symmetrical cost functions which are easily handled with a closed-form mathematical technique.

The grid method contains two major assumptions. However, through proper selection of the parameters of the grid, the effect of these approximations can be minimized. The first assumption is that there is a finite size "don't care" region. The second is that all applicable data is contained in the grid. Each of these will now be discussed.

Assumption 1: There exists a finite sized "don't care" region. It is fairly obvious that such a region exists. If the pilot is navigating a ship of 40-ft beam in a 1/4-mile wide channel, his decisions will not be influenced by an unknown error in position of a few feet. The size of this "don't care" region directly influences the required resolution for the grid method. After a discussion of the grid method which follows, a more detailed explanation of the required relationship between the "don't care" region and the grid resolution will be given.

Assumption 2: All applicable data are contained in the grid. This is the "don't throw out the baby with the bath water" restriction. If, in every time step, the a posteriori probability space is analyzed over the entire waterway (from land on the port side to land on the starboard side, and from harbor entrance to dock), then all conceivable locations to which the pilot might estimate his current location, would have been analyzed. However, the amount of computation required to support this analysis would be prohibitive, since computation time increases faster than the square of the number of resolution boxes analyzed. The number of resolution boxes in the grid is determined from the overall size of the a posteriori probability space being analyzed and the size of the "don't care" region. The minimum requirement for the size of the a posteriori space to be analyzed is determined from the requirement that the perceived fix is always contained within it. There is an additional requirement that enough additional data be included to allow analysis of the pilot confidence in the perceived fix, since this will also influence his decision. A more precise specification of the size of the a posteriori region to be analyzed will be given later.

### A.5.3 The Grid Method - Description

The description given for the grid method will focus on a bearings only observation of two ANs. Following the description of the fundamentals for this example, the procedure for handling dead reckoning, one AN observation of bearing, more than two AN observations of bearing, range observations, and other types of fixes will be described.

The starting place is the actual situation. FIGURE A-4 shows an actual situation where a ship is approaching a gate and has only those two ANs in current observation. The angles  $\alpha_1$  and  $\alpha_2$  are the actual relative bearings to AN No. 1 and AN No. 2, respectively. The pilot cannot determine the exact angles  $\alpha_1$  and  $\alpha_2$ , but instead he makes an observation on each AN. These observed bearings,  $\beta_1$  and  $\beta_2$ , are drawn from the a priori distribution of observations given the actual angles  $\alpha_1$  and  $\alpha_2$ . The a priori distribution describes how accurate a pilot's bearing observations actually are. This is obtained from CAORF data and/or at-sea data. FIGURE A-5 shows how the pilot would use the known actual positions of the ANs and the observed bearings to obtain a perceived

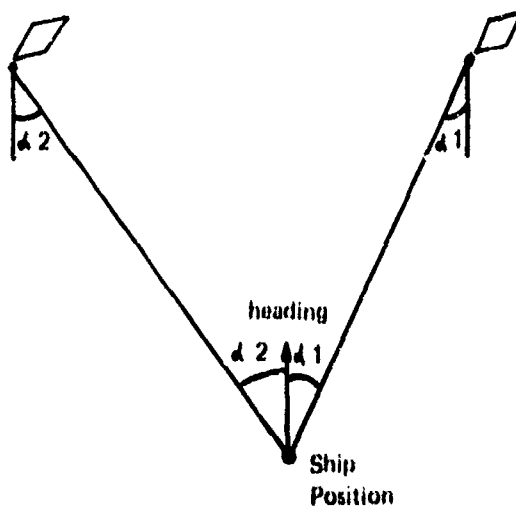


FIGURE A-4. ACTUAL SITUATION

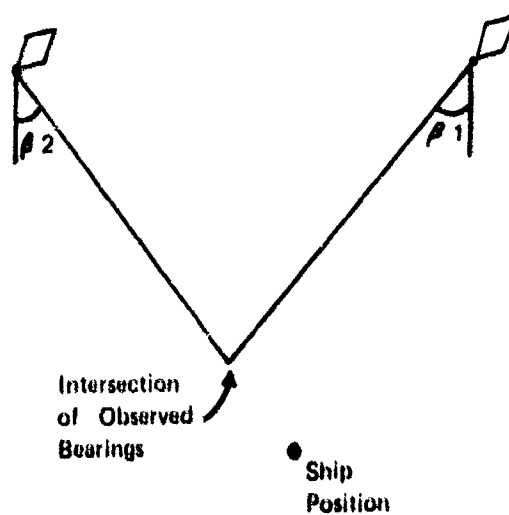


FIGURE A-5. OBSERVED SITUATION

intersection of observations. In the absence of any other information, this intersection will be the perceived fix.

The next step in the procedure is to determine the a posteriori probability density for each of the observed bearings. Since these two observations are independent, the product of the a posteriori probabilities of each possible bearing combination is the a posteriori probability of the fix. The bookkeeping procedure for handling these a posteriori probabilities is the grid method.

A rectangular grid is established around the actual ship position containing several square boxes. Each box is sized to the required grid resolution (in yards) and the overall size of the grid (in yards) is sufficient to contain all significant information from the a posteriori probabilities. Each box is characterized by its X, Y location and a single number equal to the a posteriori probability that the pilot's nominal position on the ship is located within the box. FIGURE A-6 shows the grid and the way the a posteriori probabilities of these two observations would be placed across the grid. For example purposes, the a posteriori probabilities are not shown as continuously differentiable functions, although the model can handle both smooth and stepped probability densities. A number is assigned to each box in the grid which is the product of the a posteriori probability that observation No. 1 says the ship is within the box, and the a posteriori probability that observation No. 2 says the ship is within the box. Following the assignment of these numbers to each box, the grid is normalized. The number in each box is multiplied by the appropriate constant to make the sum of the numbers in all boxes equal one. These normalized numbers represent the a posteriori probability that the ship is within each box. For the example given, FIGURE A-7 shows the a posteriori probabilities which would be placed in the grid. It should be noticed that, since the maximum of the a posteriori probability density for each observation occurs on the observed bearing, the maximum of the a posteriori probability of fix location occurs at the intersection of the observed bearings. That is, in this example, the perceived fix will be the intersection of the observed bearings, as was indicated earlier.

a. Prior Knowledge. This model is constructed so as to allow one type of prior knowledge before the fix is taken. This is the dead reckoning (with wind-current effects correction) performed on the results of the previous fix. This dead reckoning output is treated as a prior probabilistic specification on the grid. The a posteriori box values resulting from each observation are multiplied by the numbers already in the boxes from dead reckoning to yield the net a posteriori distribution - which includes both the observation and the prior information. When the largest mode of the net a posteriori probability density is taken, the result is termed the Maximum Likelihood Estimate (MLE). This is where the pilot thinks the ship is located when he incorporates all available information - both prior knowledge and a posteriori knowledge based on current observation.

a. Single Observations. Since the grid already contains the prior knowledge from dead reckoning, a single observation of a bearing only is easily taken by the procedure outlined above and the result of this single observation will be a probabilistic grid with an internal maximum. Without the prior knowledge, there would be no unique point which the pilot could judge as his present location, since the a posteriori distribution on the observation specifies a bearing line only. This is extremely important, since reduced visibility may result in only one AN being observed. Even when several ANs are visible, only one may be observed at a time; that is, the pilot does not normally take a chart and plot the triangulation fix, but sequentially incorporates what each AN tells him about his position. This procedure duplicates the sequential process.

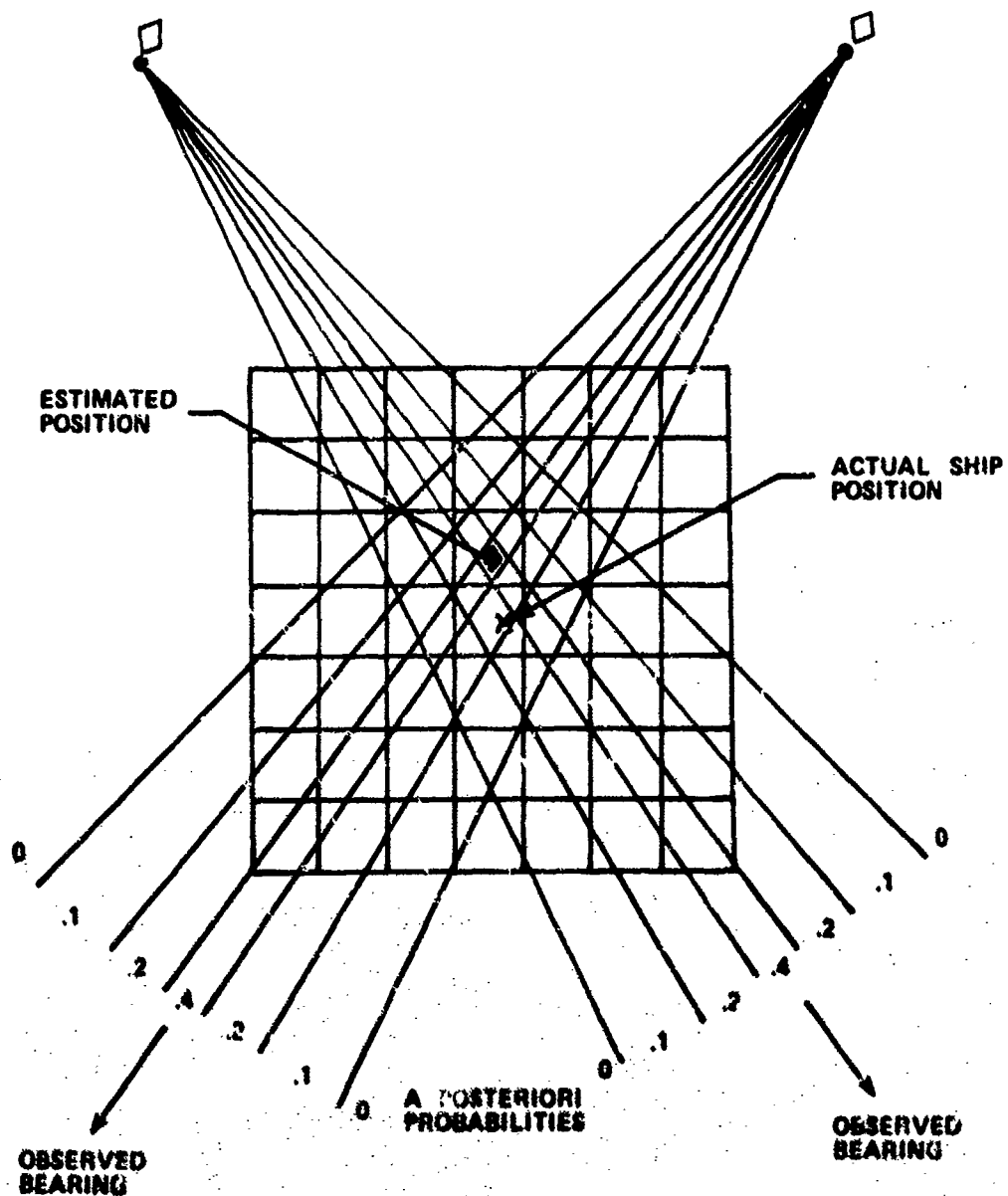


FIGURE A-6. GRID FOR TWO BEARING OBSERVATIONS. EXAMPLE - DISCRETE PROBABILITIES



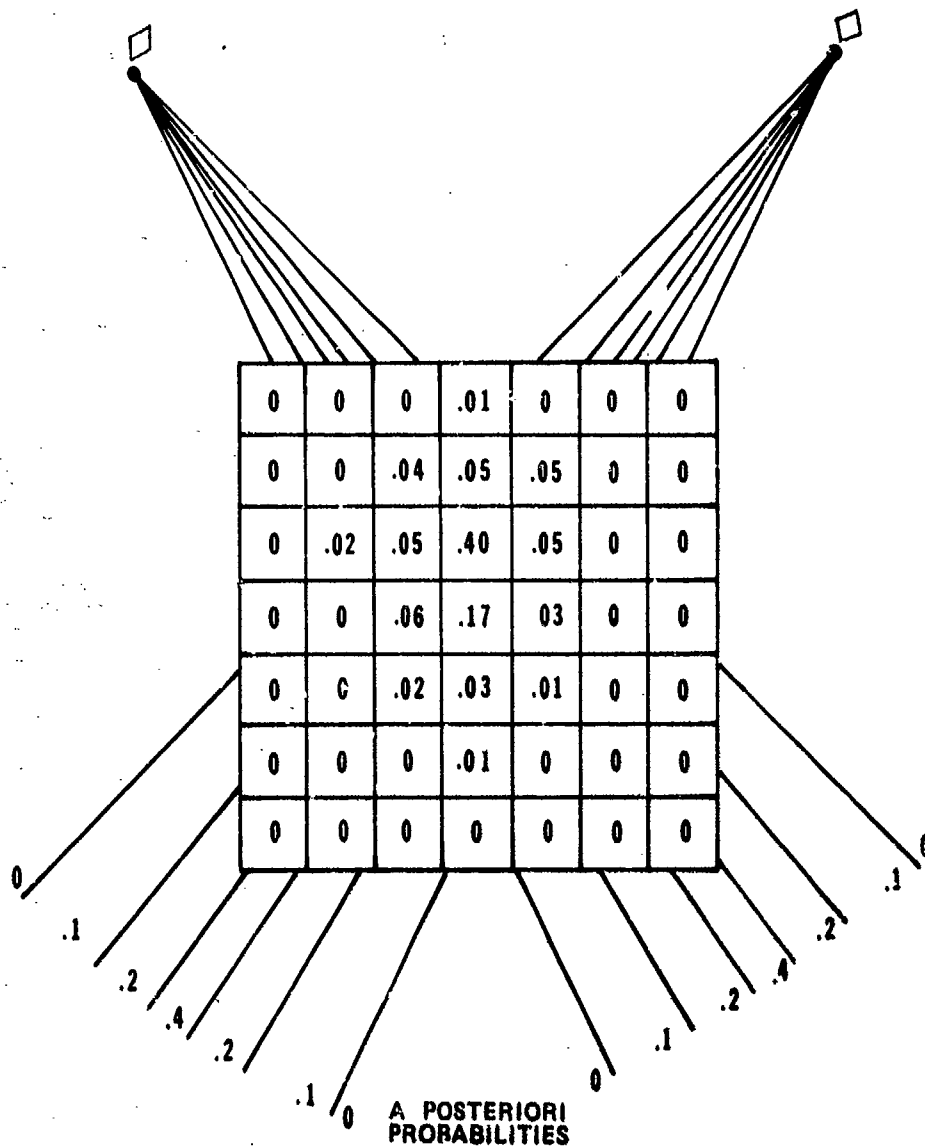


FIGURE A-7. GRID FOR TWO BEARING OBSERVATIONS. EXAMPLE - VALUES ARE PRODUCT OF A POSTERIORI PROBABILITIES IN EACH BOX FROM EACH OBSERVATION, THEN NORMALIZED

c. More Than Two ANs Observed. If three ANs were observed at the same time, the most likely intersection of the observed bearings is three different locations, as is indicated in FIGURE A-8. In this case, the usual procedure is to take a center of gravity point between these three intersections. The weighting to determine the center of gravity is related to the a posteriori variance of each observation. To be more precise, this is the maximum likelihood fix, given that the a priori probability densities are Gaussian. The grid method is more general, since it provides direct computation of the maximum likelihood fix without any assumption on the shape of the a priori probability densities. The procedure is identical to that described above. The a posteriori distribution for each observation is multiplied on the grid and the peak value is selected after all available information is included. In the case of Gaussian distributions, the result is the same as the result obtained by the conventional algorithm; however, when the distributions are not Gaussian, the grid method will still yield the maximum likelihood estimate of the fix, whereas the conventional procedure may not.

d. Range Observations. Range observations are handled with the same procedure previously described. The a posteriori distribution around the observed range is determined and its effect is multiplied onto the grid.

e. Other Types of Fix. The previously described procedure completely covers ANs which are observed from the ship, whether by radar, visual, with or without binoculars, using a pelorus, or not. Other ANs can also be handled by the general grid method. The procedure is to determine the a posteriori probability density around the fix and to multiply it onto the grid. Hyperbolic fixes (such as LORAN) and/or OMEGA are easily accommodated in this fashion. FIGURE A-9 shows how some of these other types of fix involve different geometries for grid information.

When all available information is multiplied onto the grid, the result is normalized and the numbers in the boxes are the a posteriori probability density of the pilot's position on the ship being within each specific grid box. The various ways this a posteriori probability can be used to estimate fix are described later. For example, the location where the grid has maximum probability is the maximum likelihood estimate.

#### A.5.4 Fix Objectives

In the introduction to Section A.5 four primary objectives of the fix technique were outlined. They are that the fix techniques be selected to handle:

- a. Visual observation of a bearing to an aid;
- b. Multiple observations of bearings and/or bearings and ranges which may not be consistent in fix location;
- c. Shoals, submerged wrecks, etc, which would modify the risk the pilot takes if his positional estimate is incorrect; and
- d. Ship equipment and electronic aids (radar, radio, pelorus, etc).

The first two were discussed in the previous section. The grid method for estimating the net a posteriori probability in each time step handles these cases. The use of a cost/risk function to obtain the risk of incorrect decision will be described in the section on estimation techniques using the grid. This procedure will lead to performing the Bayes minimum risk decision which directly handles the third objective.

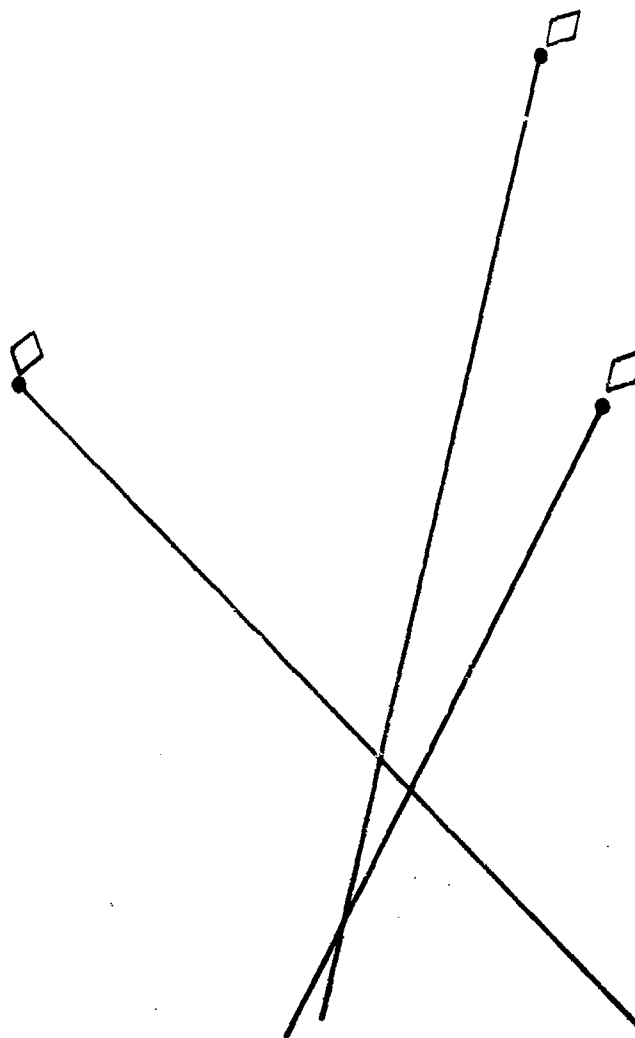
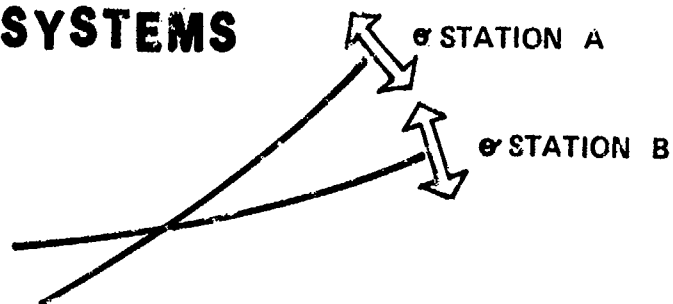
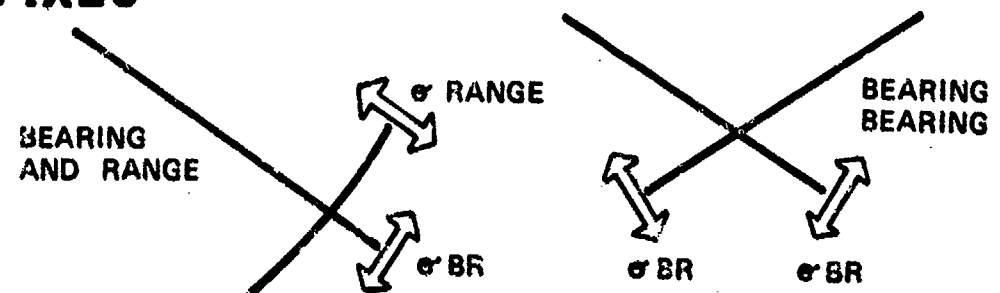


FIGURE A-8. THREE ANs - TYPICAL INTERSECTION OF OBSERVED BEARINGS

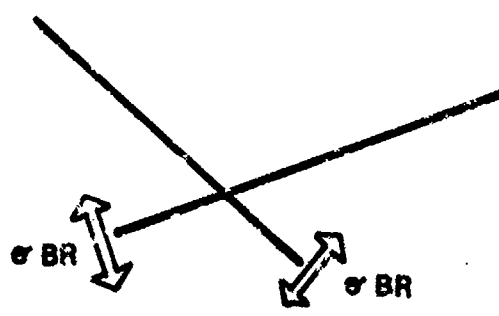
## HYPERBOLIC SYSTEMS



## RADAR FIXES



## PELORUS



## VTS

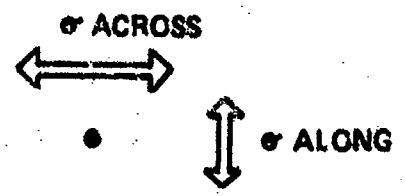


FIGURE A-9. SHIP'S EQUIPMENT FIXES

The grid method directly accomplishes the outlined objectives of the fix model and simultaneously allows for the use of actual measured probability distributions, rather than forcing them to be of mathematical types which can be handled in closed form solution. The grid method takes longer to run on the computer than closed form analytical procedures, but the point-exhaustive approach which it represents is the only procedure which is expected to indicate actual ship behavior.

#### A.5.5 Information in Grid - The Various Models

The discussion thus far has centered on the grid containing the net a posteriori probability resulting from the combination of dead reckoning (prior information) and the present observations. This description applies to the overall navigating and steering model which is the primary output of the current effort. However, there are also other specific models which are included as part of the AN evaluation system. Each of these models serves to answer a specific question, and the use of all of these models provides considerably more information than the use of a single model. The differences between these models are twofold: first, what is contained in the grid; second, what are the fix results and how are they used. Here we will specifically examine each model and address these differences.

a. Fix Model. The objective of the fix model is to determine the tightness of fix available from the ANs. This is a static problem which assumes the ship is "placed" at a specific location in the channel with no prior knowledge (dead reckoning). The grid is then filled with the a priori probability densities resulting from taking an observation of each visible AN. The result which appears on the grid is the probability that each specific X, Y location will be the intersection of the observations; i.e. the probability that the pilot would think he is there given no previous knowledge. The variance in each direction represents a measure of the amount of information which the specific AN type and geometry supplies to the pilot. No a posteriori calculations are made in the fix model.

b. Static Piloting Model. The objective of the static piloting model is to determine the distribution of fix confidence which would occur from a single observation of the AN configuration. This is also a static problem in which the ship is placed at specific locations in the channel. However, in this model, a ship track is specified and several specific locations for analysis are located along this track. The grid is filled with the a posteriori probability density assuming the observed value is the actual value. The position of the maximum a posteriori probability (MAP) shows whether a difference in parameter bias (a priori) and observation bias (a posteriori) exists; that is, whether or not there is a natural bias error due to the pilot's estimation process. In addition, the variance of the results in the cross track and along track directions provides a measure of the pilot's confidence in fix accuracy.

c. Dynamic Piloting Model. The objective of the dynamic piloting model is to determine the distribution of fix confidence which would occur when the ship follows a prescribed track. The human behavior of perseverance, dead reckoning, and forgetting are included in the way they affect the a posteriori probabilities. The grid is filled with the net a posteriori probability of fix at each location assuming the observations on the ANs are the actual values and that the dead reckoning uses actual ship water speed and course. The position of the MAP estimate shows whether a net bias error exists in the combined observation and dead reckoning procedures. The variance of the results in cross track and along track directions provides a measure of the pilot's net confidence in fix accuracy. The a posteriori grid from the previous time step is mapped through the dead reckoning algorithm to give the prior knowledge which the pilot has at the present time step.

d. Navigating and Steering Model. This is the primary model of this effort. A major objective of the navigating and steering model is to determine the ship track distribution which results from the AN configuration. This is a dynamic model in which each observation of an AN is drawn from the a priori distribution (parameter space) and the DR involves inexact initial knowledge of wind and current effects and a learning process to make these estimates better as further fixes are available (with instrument errors on the heading information and inexact knowledge of the speed through the water continuing throughout the problem). The previous net a posteriori grid is dead reckoned and the results of this DR form the prior knowledge the pilot has before the present observation. FIGURE A-10 shows, in simplified manner, how the DR fix grows with time. The observations and the a posteriori probabilities around these observations are multiplied onto the previous grid to yield the net a posteriori probability. This grid is then manipulated by the cost function weighting to yield the risk grid upon which the pilot performs the minimum risk decision as to fix location. The variance of the net a posteriori grid around the fix is a measure of the pilot confidence in the fix. Using the minimum risk decision point and the confidence, the pilot performs steering decisions which are carried out by the helmsman to result in a ship track. Multiple traverses of the channel are simulated and the ship track distribution is obtained as a function of ship location along the channel. The ship track distribution is a primary measure of the effect of different AN configurations.

#### A.5.6 Estimates of Position

There are numerous techniques which can be used to estimate position based on DR results and present observations. The grid method is only a bookkeeping algorithm to allow the selected technique to be performed. One technique is to multiply the a priori probabilities to obtain the probability that a specific point will be selected as a result of the observations. This technique answers the wrong question. The question which the pilot must answer by the estimation technique is, "what is my actual position given that these observations were made"; not, "what is the probability of a given observed position given that my actual position is known?"

The principal techniques focus on the question to be answered. They involve computing the a posteriori probability built around each observation and computing a fix based on this probability. An earlier section of this report focused on the differences between prior and posterior probabilities and what they represent. Another section described how the posterior probabilities are calculated for the grid. This section focuses on how to use these posterior probabilities to calculate the estimated position of the ship upon which the pilot makes his steering decisions.

The "as-if" behavior is the assumption applied to the pilot. He behaves as-if he actually performed the complicated calculation described by the model. In general, that is true. A human will exhibit the as-if behavior tending toward the optimum performance even though he is not going through the identical calculations. There is a slight degradation due to actual human behavior (optimized computer-driven procedures make slightly more efficient use of the available data); however, it has been determined that in most cases the best model of human behavior is to calculate the optimum and degrade it rather than to attempt direct computation of suboptimal behavior. This is why supply-demand computations in micro-economics are considered valid. The assumption behind supply-demand is that total market information is known to the purchaser, which is not true. However, the consumer behaves as if he has that information with a small degradation in the final result. It is this type of "as-if" behavior which is attributed to the pilot in this model. Therefore, the various optimized techniques for estimating present own ship location will be presented and the selected one will be indicated.

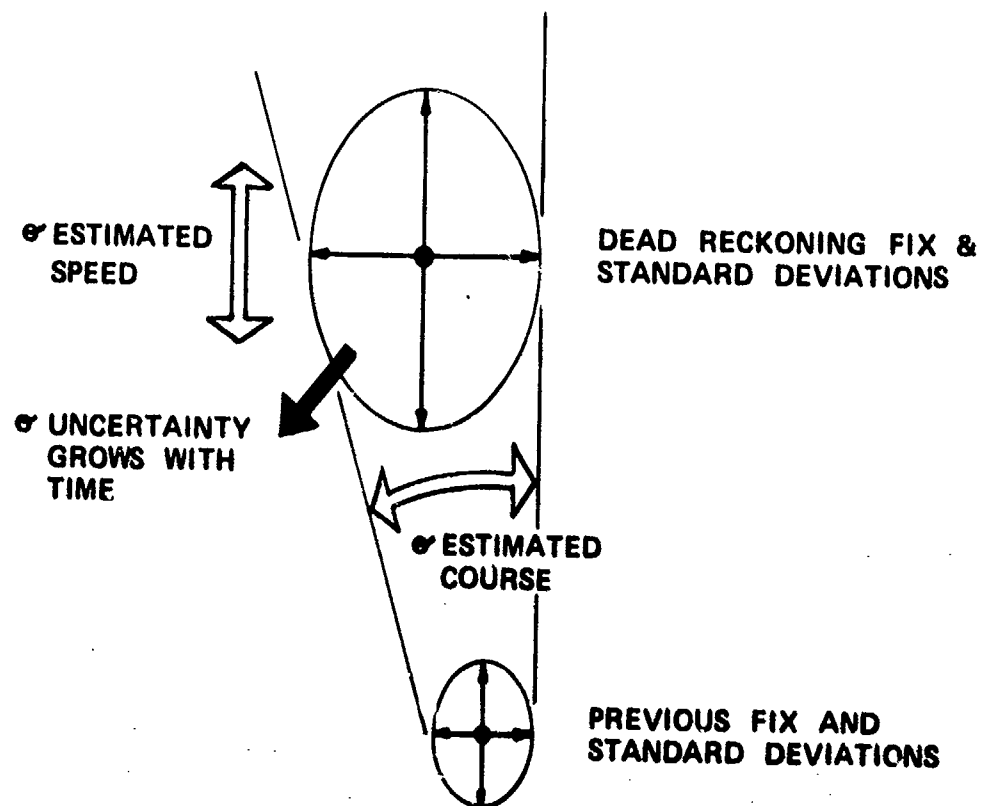


FIGURE A-10. DEAD RECKONING FIX

a. Maximum A Posteriori Probability (MAP) Estimate. The MAP estimate is the position where the a posteriori probability of location is a maximum. It relies on the fact that the a posteriori probability at each position represents the probability that that position was the true value given the observations. In the absence of any other information which would affect fix (i.e., all available information is already included in the a posteriori probability), this procedure states that the pilot should estimate his position at the location where it is most likely to be. As is generally applied, the MAP estimate is built around the observations only and not on prior information. That is why we have reserved the phrase, "net a posteriori probability," for the composite of DR and observation, and the phrase, "a posteriori probability", for the observations only. The MAP estimate, therefore, is based only on the observations, which is the result required for the static piloting model.

b. Maximum Likelihood Estimate (MLE). The maximum likelihood estimate is the maximum of the net a posteriori probability. As was just described, this is the place where the ship is most likely to be, given both the observations and the DR (prior knowledge). It can be seen that the MAP estimate and the MLE are identical when no prior knowledge exists, and that the MLE is simply the MAP estimate applied to the net a posteriori probability. This is the estimating procedure applied to the dynamic piloting model.

c. Minimum Mean Square Error Estimate (MMSE). The minimum mean square error estimate can be approached in two ways. First, it is the mean of the a posteriori probability density. By this description, it can be shown to be that value which yields the lowest variance in a posteriori probability around the estimate. Any other selected location will have a greater variance around it. If the cost of an error in fix (the risk associated with a fix error) increases linearly with the square of the error, this would be the estimate which minimizes the overall risk taken. Therefore, the second description of the MMSE estimate is the technique which minimizes the risk when the cost of error is proportional to the square of error. This is simply the Bayesian minimum risk algorithm applied to a specific cost function. The Bayesian minimum risk technique will be described next. The disadvantage of selecting the MMSE estimate for a bimodal, a posteriori probability density, can be described by a simple example. Suppose the pilot is navigating an area around a shoal or wreck. He can pass either to the right or to the left and be safe. If there are buoys indicating both passages, but only one set is presently observed due to weather conditions, the a posteriori distribution will have several modes (peaks), depending on which set of buoys he assumes he sees. The obvious answer for his dilemma is to assume one of the sets and to use the MLE for decision. If he uses the MMSE, although the variance of error is minimized, the probability of hitting the shoal or wreck is maximized, since the MMSE selects a position between the modes. The flaw here was that the cost of error function is not proportional to the square of error; therefore, the pilot is not selecting his minimum risk solution by using the MMSE.

d. Bayes Minimum Risk Estimate. When applied to the grid method, the Bayes minimum risk estimate is straightforward to perform, although tedious to calculate. There a cost function is applied to each box under the assumption that a specific box ( $X_1, Y_1$ ) is the actual location. The net a posteriori probability that the ship is in each box is multiplied by the cost of being in that box when box ( $X_1, Y_1$ ) is the actual location. This "risk" is summed to the risk for all other boxes in the grid to get the total risk of assuming that ( $X_1, Y_1$ ) is the actual ship location. This calculation is performed for all boxes in the grid, each time assigning a risk to being in each box assuming the new ( $X_1, Y_1$ ) is the ship location. The Bayes criterion says to select the location which contains the minimum



overall risk of error. As was already indicated, when the cost of error is proportional to the square of the error, the MMSE will be the resultant Bayesian estimate. When all errors have the same cost (the cost is independent of the magnitude of the error), the Bayes minimum risk algorithm will yield the Maximum Likelihood Estimate (MLE). Therefore, it can be seen that the assumed cost (or risk) function directly influences the selection of the estimate. When applied to the navigation problem, in the absence of traffic, the cost of being closer to the edge of the channel will be more than the cost of being nearer the center of the channel. Shoals and wrecks will have a very large cost associated with them. The cost of along track error will not be significant until a maneuver is required (along track error before a turn becomes cross track error during and after the turn). Therefore, a different cost function will be assigned to each leg in the model. The pilot selects his fix location to be the minimum risk solution for that leg with the a posteriori probabilities which exist at that time. This is the procedure which is applied to the navigating/steering model, since it is considered to best represent the actual decision process which the pilot uses. It is a conservative position estimate in terms of risk.

#### A.5.7 Fix Technique Summary

The procedure by which the pilot combines the observed ranges and bearings to each observed AN with the information which comes from the DR and with the risk of being wrong is the "fix" technique. The grid method is a point-exhaustive approach to calculate the a posteriori probability of actual location using both the prior knowledge from dead reckoning and the present observations. The size of a box in the grid is termed the grid resolution. The "don't care" accuracy region is  $1/3$  to  $1/5$  the grid resolution because a smoothing algorithm will be used on the final risk to determine the local minimum. It is expected that this smoothing algorithm will have an accuracy of  $1/10$  the box size. The number of boxes required can be determined by running the fix model at locations where the static fix is expected to be worst and setting the number of boxes to three sigma as determined at these locations. Since DR improves the fix accuracy, the dynamic model should contain the observation, as well as enough additional information to obtain the sigma around the a posteriori probability (confidence) as desired. The boxes in the grid are square with size equal to the grid resolution. The total grid is rectangular with a sufficient number of boxes in each direction to contain the along track and the across track information.

The DR information is treated as prior knowledge of position and the associated probabilities are assigned to each box in the grid. The present observations are mapped onto the grid by taking the observed value and the a posteriori probability of actual value around the observed value. This a posteriori probability, after being scaled for the influence of perseverance by taking the  $1/\rho$  root of the probability values ( $\rho$  is the perseverance factor), is multiplied onto the grid. The net a posteriori probability is the grid information following the combination of all present observations with the prior knowledge and a posteriori distributions from other types of fixes. A cost function is assigned to error in observation using the specific parameters of each leg and the traffic present. The risk is calculated using a Bayesian technique and the minimum risk location is selected by the pilot as his fix. The a posteriori probability grid is then used to calculate the pilot confidence by computing the variance of data around the selected fix. These parameters (the fix location, the risk at that fix location, and the pilot confidence in the precision of that fix) are used in the decision-making algorithm which is next in the model. The a posteriori probability grid is also combined with the perceived course and ground speed (and the variance around these values) to obtain the new dead reckoning input for the next observation.

The described fix technique handles cases of limited visibility; multiple aids to navigation even when their observations do not intersect at a single point; other types of fixes whether internally created on the ship or externally supplied to the ship; and decision-making in the presence of traffic, shoals, wrecks, and other factors which would influence the pilot's estimate of risk.

## A.6 DECISION/ACTION LANGUAGE

### A.6.1 Introduction

The concept of inputting a logic structure (as opposed to hard data) is a unique feature of the navigating and steering program. This feature gives the program almost unlimited flexibility and applicability to model the widely divergent types of scenarios that are part of any inclusive study of the role of ANs.

Different scenarios require different physical channels, different ship types, different weather conditions, and different AN types and configurations. However, it is also important to model different piloting philosophies, different levels of pilot skills and confidence, and different ship-handling capabilities. Especially in the future, when new fix methodologies are defined, new electronic aids are made available, and more elaborate harbor control exists, it will be essential to be able to model the role of the pilot. Because only through their effect on the pilot are advances in one area (ANs) made apparent in other areas (ship safety, increased traffic flow).

The navigating and steering program uses English-like sentences to model the pilot's decision-making logic and ship-handling orders. This English structure is an input to the program and can be changed from run to run without the need for any change to the program itself.

The distinction between the decision and action functions might seem unclear at first, and seem to overlap because both involve some decision making. It is true that the limits of these two functions are indeed indistinct and they do overlap in some cases. However, the philosophy of modularizing the program by functions dictated that these two areas be kept separate. The basic distinction between the decision and the action functions is that the decision function describes the pilot's broader operational policy decisions, and the action function describes the pilot's ship-handling decisions. The decision logic determines what the broad situation is from the information and estimates available to the pilot. The action logic describes how the pilot actually carries out the maneuver decided upon. A limited decision process is needed for these maneuvers.

### A.6.2 Decisions

a. Decision Language. A decision language had to be developed that would be tailor-made for the AN application. That is, it had to be structured to handle the type of logic required in the piloting process. The language also had to be structured to make it easy to describe simple decisions and yet have the scope and flexibility to handle the complexity required for a sophisticated problem.

Such a language has been developed. The language consists of a vocabulary (key words and phrases that are recognized by the program) and a syntax (rules for structuring these key words or phrases into sentences recognized by the program). These sentences

are called commands and a group or a paragraph of these sentences is called a block of commands.

An example of a command in the decision language is:

IF RANGE TO AID 3 < 500 YDS, START TURN: START LEG 2.

In this language, the syntax and many key phrases are presently defined. However, any key phrases not defined at present, but needed to test certain conditions, can be easily added as the need arises.

Moreover, the exact wording of the key phrases may be changed from run to run, as long as the meaning of the phrases remains the same. For example, one user might feel more at home with the expression:

DISTANCE TO BUOY 3

Than with the expression:

RANGE TO AID 3.

The syntax translator which is part of the input module interprets the English-like decision commands and converts them into a matrix of numbers. This matrix of numbers is used by the decision module, which executes the commands by making the appropriate tests on program variables (e.g., range to aid 3) and keeping track of the logic flow (i.e., which command should be executed next).

Following is an example of a decision block which serves to illustrate some of the features:

- (1) TEST FOR TURN:
- (2) IF ABEAM AID 3, TURN; TEST FOR END.
- (3) IF TIME = 30 MINS, OR VISIBILITY < 1000 YDS, RADAR ON; TEST FOR TURN.
- (4) IF TIME = 45 MINS, TURN, LOAD CHART 1; TEST FOR END.
- (5) OTHERWISE STRAIGHT CHANNEL.
- (6) TEST FOR END:
- (7) IF HEAD = 202 DEGREES, END TURN

This example illustrates a way of continuing down a straight channel (line 6), meanwhile checking for when to start a turn. The turn should be started (action block TURN) whenever aid 3 comes abeam (line 2). As soon as this condition is met, the next decision logic (block TEST FOR END) is started to check for conditions on which to end the turn (lines 6 - 7). If the ship has not come abeam of aid 3 by 30 minutes or if the visibility is less than 1000 yards, the action block RADAR ON should be started, and continue decision block TEST FOR TURN to keep checking for aid 3 (line 3). If, for some reason, the ship has not come abeam of aid 3 by 45 minutes, start action block TURN anyway, record that fact in chart No. 1, then start checking for end of turn (line 4).

This example illustrates several features of the decision language:

1. It uses word labels instead of numbers so that it is self-documenting. For example, the word TURN in line 2 means execute action block with label TURN. This is instead of DO ACTION 10. The phrase TEST FOR TURN in line 3 means start with decision block labeled TEST FOR TURN at next time step. Each action or decision block has a word label which is addressable.

2. The logic is sequential, based usually on conditions or passing time. For example, once aid 3 comes abeam, the pilot stops checking for it and goes on to other considerations (TEST FOR END).

3. Several conditions may be checked for at once. For example, the pilot is checking for aid 3 abeam or time = 30, or visibility < 1000, or time = 45. If any of these conditions are met, an action is specified. If none are met, the action specified by the OTHERWISE command (line 5) is executed — in this case "STRAIGHT CHANNEL".

4. Multiple conditions can be checked for. An action may be desired only IF A AND B are both true, or IF A OR B is true. In line 3, the same action (RADAR ON) is done and the same decision block indicated (TEST FOR TURN) if time = 30 minutes OR if visibility < 1000 yards.

5. The fact that certain conditions have or have not occurred may be of significance in analyzing the scenario or comparing different scenarios. Thus, the user has the ability to specify for each run what statistics he wants collected and on what conditions. The LOAD CHART/COUNTER/HISTOGRAM phrase (line 4) will collect the data as specified in the input. This would most likely be in addition to the data automatically collected for each run.

6. The action block that is referenced most likely contains several commands that are executed in order separated by lengths of time. So that the action sequence is not interrupted each time the same condition is encountered in the decision logic, if the decision command references the same action block that is already being executed, the block will not be started over. Thus, every time the OTHERWISE STRAIGHT CHANNEL decision command is executed in a row after the first time, no new action command is specified and execution continues within the STRAIGHT CHANNEL action block.

b. Decision Syntax. In the syntax illustrated, items in parentheses are optional, words in capital letters are keywords to be used as is, words in quotes describe words or phrases to be supplied by the user, and words in lower case letters without quotes describe numerical quantities to be supplied by the user. The proper punctuation is important and should be used as shown.

The following rules or notes apply to the decision language syntax:

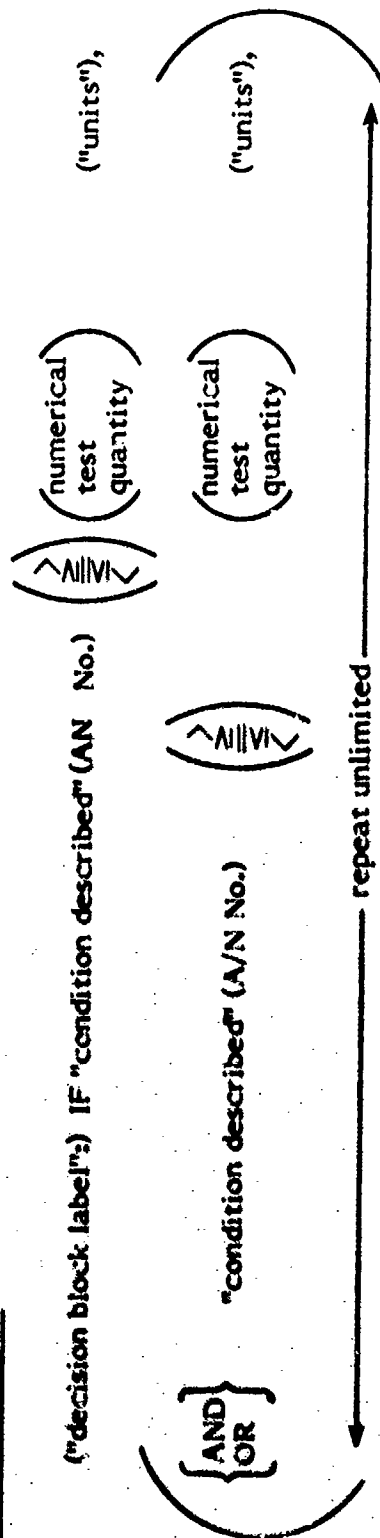
1. "Condition described" refers to one of the test conditions which has been previously defined in the vocabulary and is thus recognized by the program. This phrase may be any length, but must match exactly the phrase as listed in the vocabulary. If no exact match occurs, the closest match is used, but a warning is issued requesting a correction.

See the list of decision conditions in TABLE A-3.

2. AN No. refers to the number of a specific aid or a class of aids (e.g., buoys).

TABLE A-3. DECISION SYNTAX

Type 1 "IF" commands



"action block label" ( , LOAD { CHART HISTO COUNTER } number )

(; "decision block label")

Type 2 "OTHERWISE" commands

OTHERWISE "action block label" ( , LOAD { CHART HISTO COUNTER } number )

(; "decision block label")

3. "Units" must be a unit defined in the vocabulary list so that it is recognized by the program. If no units are specified, a default set of units is used.

4. Any number of AND or OR phrases are allowed.

5. The AND and OR phrases are combined sequentially, instead of following the Boolean rule of combining ANDs before ORs. That is,

IF X OR Y AND Z

is the same as IF ( (X OR Y) and Z).

6. The "action block label" is any user-written label of up to 18 letters. The label on the action block must match this exactly. This label should be chosen to be descriptive of the action involved.

7. The "decision block label" is any user-written label of up to 18 letters. If no decision block label is given on a decision command, the default will be the name of the decision block presently being executed.

8. If no OTHERWISE command appears at the end of the decision block, or if an OTHERWISE NO CHANGE command appears, the action block presently being executed is continued without interruption.

9. There may not be more than one OTHERWISE command per decision block and the OTHERWISE command must be the last command of the block.

10. Decision blocks may be typed in free format because blanks and carriage returns are ignored.

11. No continuation characters are needed for continuing a command on the next line.

12. No descriptions (labels, units, condition) may contain anything but letters.

13. The "action block labels" may not start with the letters IF, OR, or NOT.

IF INSIDE PORT BOUND

" INSIDE STARBOARD BOUND

" OFF TRACK TO PORT

" OFF TRACK TO STARBOARD

" RANGE AID

" BEARING AID

" BEAM AID

" SIGHT AID

" VISIBILITY

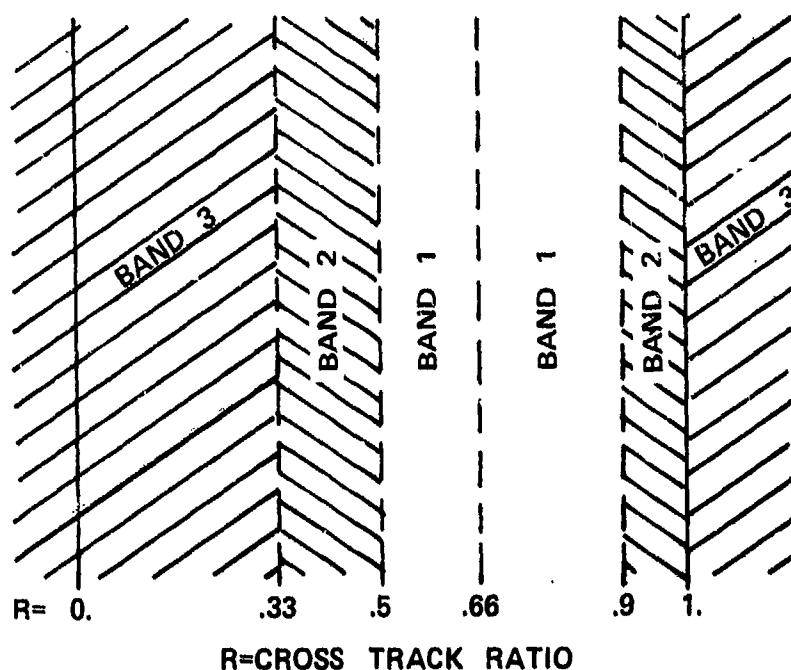
" SEASTATE

" TRAFFIC DENSITY

- " ALONG TRACK FIX CONFIDENCE
- " ACROSS TRACK FIX CONFIDENCE
- " ON RANGE

b. Example Showing Decision Logic in a Straight Channel. This type of logic could be used in a channel of any width because the decisions are based on the pilot's estimate of the ratio of his distance across the channel to the channel width (i.e., 0 is the port side of the channel, 1 is the starboard side, 0.5 is the centerline).

In this case, the pilot's plan was to adjust his course to the desired course when he is inside band 1, and try to get the ship back on the track (which is 2/3 of the way across the channel) when he is in bands 2 and 3. From band 3 he will order a more drastic correction than from band 2.



#### STRAIGHT CHANNEL:

- IF CROSS TRACK RATIO > 1, STEER TO TRACK FR SB.
- IF CROSS TRACK RATIO > .912, CORRECT SB ERROR
- IF CROSS TRACK RATIO < .33, STEER TO TRACK FR PORT.
- IF CROSS TRACK RATIO < .5, CORRECT PORT ERROR
- OTHERWISE ADJUST COURSE

Examples of simple and complex commands (sentences) allowed with this syntax are:

TEST FOR SHALLOW: IF RANGE TO AID  $3 < 1000$  YARDS,  
AND BEARING TO AID  $3 \geq 270$ , AND BEARING TO  
AID  $3 \leq 90$ , SLOW DOWN, LOAD COUNTER 6;  
TEST FOR EDGE.  
IF DISTANCE FROM START OF LEG  $> 1.5$  MILES, TURN ON RADAR.  
IF OFF TRACK  $> 100$ , CORRECT; TEST POSITION.  
OTHERWISE STOP.

d. Decision Conditions. Presented below is an incomplete list of conditions which may be tested by decision commands. The exact phrase used to describe the condition may be changed according to the user's preferences. Additional conditions are easily added to the program structure.

IF TIME  
" TIME SINCE START LEG  
" TIME IN BLOCK  
" ESTIMATED LATITUDE  
" ESTIMATED LONGITUDE  
" ESTIMATED LEG  
" ESTIMATED HEADING  
" ESTIMATED COURSE  
" ESTIMATED SPEED OVER GROUND  
" ESTIMATED SPEED OVER WATER  
" ESTIMATED CROSS TRACK POSITION

#### A.6.3 Actions

a. Action Language. An action language had to be developed that was structured to handle the logic used and the orders given in the navigating and steering process. The language had to include some decision-making capability, but at the more straightforward and concrete level used in ship-handling (as opposed to policy) decisions. The language also had to include orders for maneuvering and handling the ship, getting information from various sensors (radar, RDF, pelorus), changing the confidence the pilot places in various sensors and/or methods of fixing, etc. In short, the action language had to provide the interaction between the pilot and crew, pilot and ship, pilot and outside world.

As with the decision language, the action language had to be structured to make it easy to handle straightforward problems and yet have the scope and flexibility to handle any level of complexity.

Such a language has been developed. As in the decision language, the action language consists of a vocabulary (key words and key phrases that are recognized by the



program) and a syntax (rules for structuring these key words or phrases into sentences recognized by the program). These sentences are called commands, and a group or paragraph of these sentences is called a block of commands.

Two examples of commands in the action language are:

STEADY ON COURSE, 5 MINS.

UNLESS CROSS TRACK VELOCITY > 0 KNOTS; LEFT RUDDER.

In this language, the syntax and many key phrases are presently defined. However, any key phrases not defined at present can be easily added as the need arises. The exact wording of the key phrases that describe the orders may also be changed from run to run as long as the meaning of the phrase remains the same. For example, the user might feel more at home with the expression UNLESS STARBOARD DRIFT than with the expression UNLESS CROSS TRACK VELOCITY > 0 KNTS.

The syntax translator which is part of the input module interprets the English-like action commands and converts them into a matrix of numbers. This matrix of numbers is used by the action module, which executes the commands by making the appropriate tests on program variables (e.g., cross track velocity), initiating the orders (e.g., steady on course), keeping track of the flow (i.e., which command should be executed next), and monitoring the timing of each command (e.g., steady on course for 5 minutes).

Following is an example of an action block which serves to illustrate some of the features.

- (1) TRACK: STEADY ON COURSE, 5 MINS.
- (2) UNLESS CROSS TRACK VELOCITY > .2 KNTS; LEFT RUDDER.
- (3) UNLESS CROSS TRACK VELOCITY < .2 KNTS; NEXT
- (4) RIGHT RUDDER 5°, 2 MINS; CENTER.
- (5) LEFT RUDDER: LEFT RUDDER 5°, 2 MINS; CENTER.
- (6) CENTER: CENTER RUDDER, 1 MIN; TRACK.

This perhaps unrealistic example illustrates a pilot trying to keep on a prescribed course. He has previously estimated the effect of wind and current and picked a heading which he thinks will keep him on his desired course. In this action block, he is monitoring the ship's actual progress along the track.

The pilot checks his estimated cross track velocity (obtained from fix) and if it is greater than .2 knots in the starboard direction he decides to use a left rudder (line 2). If it is greater than .2 knots in the port direction (line 3), he decides to use a right rudder. If neither condition is true, he remains steady on his present course for 5 minutes and then executes the same action commands again to check cross track velocity.

Thus, if the present course is correct, the pilot remains on it, checking drift every 5 minutes. However, if the present course were not correct, or if wind or current changed, the ship would soon have a cross track velocity in either direction greater than .2 knots. When that happens, either the command on line 4 or line 5 is executed and a 5° rudder is initiated for 2 minutes. In both cases, the command on line 6 is then executed which

brings the rudder back to the center for 1 minute; the TRACK block is then started again. Again the cross track velocity is checked and it is either within the .2 knot limits or the rudder must be put on again.

Note that the example should have taken into account the possibility that a 5° rudder might be insufficient to compensate for current and thus never get the ship onto the desired course. Greater rudder orders might be needed.

The features illustrated by the example are:

1. Work labels are used instead of numbers so that the logic is self-documenting. For example, CENTER is used instead of ACTION 6.

2. The commands are of two types: orders (lines 1, 4, 5) and tests (lines 2, 3).

3. Any order command may have a label and thus be referenced by any other action command. For example, lines 4 and 5 reference line 6 (CENTER) as the next command to execute.

4. The label on the first command of a group is the block label as well as the command label and may be referenced by a decision command.

5. The order commands may include a time duration. If no time is specified, zero is assumed. (Some specific commands calculate their own duration, in which case no time duration need be specified.) This time gives the wait time until the next action command is executed.

6. The next action command to be executed is given after the semicolon. If none is indicated, the same command is repeated. For example, line 1 is repeated every 5 minutes. If the label after the semicolon is NEXT (line 3), the next command in order is executed, saving the need to label it.

7. Each command is executed, and then the time duration occurs. Nothing is done automatically at the end of the time duration. For example, line 5 says put on a 5° left rudder and wait 2 minutes. The 5° left rudder will remain on even after the 2 minutes unless another command changes it. In this case, line 6 brings the rudder back to center.

8. All UNLESS (test) commands are checked in order until the first one that is true is found. The command listed in the UNLESS command is then executed immediately. Only if no UNLESS commands are true is the "order" command preceding the UNLESS commands executed. For example, line 1 is executed only if lines 2 and 3 are both found false.

9. There is no limit to the number of UNLESS commands which may follow an "order". UNLESS commands may follow any "order".

10. Control passes from command to command as indicated by the labels until a condition occurs which causes the decision logic to choose a new policy or action. The decision logic will then indicate which action block to execute and the previous "next command" and wait time will be ignored.

The example above illustrated one end of the spectrum of ways to use the action language. It showed a case where the user wanted complete control over the orders for maneuvering the ship (the pilot who does it all to the point of giving every last rudder

order). This type of control over the problem is necessary under some conditions, or for some part of the entire scenario. However, it would be tedious to write out all the orders and tests a pilot makes.

Therefore, the program can handle orders at various levels of details. The more the program does, the less the user has to do. For example, the user can write action commands to give rudder orders, he can write commands to give heading orders and have the helmsman worry about the rudder, he can write commands to give course orders and have the program worry about wind and current and conversion to heading, and the helmsman worry about the rudder. Or the user can write a command that calls a pre-programmed subroutine that will make all the tests and orders necessary to get the ship around a turn. For example, the command:

MAKE TURN (ENDHEAD 150°, RADIUS 0.5 MI); NEXT.

carries the ship through a complete turn described by the parameters in parentheses (end on heading 150°, radius 0.5 mi.). In this case, the wait time need not be specified, as the MAKE TURN command will continue until the turn is complete; the next command will then be executed.

b. Action Syntax. In the syntax illustrated, items in brackets are optional, words in capital letters are key words to be used as is, words in quotes describe words or phrases to be supplied by the user, and words in lower case letters without quotes describe numerical quantities to be supplied by the user. The proper punctuation is important, and should be used as shown.

The following rules or notes apply to the action language syntax:

1. "command description" refers to one of the command phrases which has been previously defined in the vocabulary and is thus recognized by the program. This phrase may be any length, but must match exactly the phrase as listed in the vocabulary.

See the list of action command descriptions in TABLE A-4.

2. The parameters which may be included in parentheses must be in the same order and in the same units as the command description requires. This is primarily for subroutine-type commands. Thus, if the MAKE TURN command expects 2 parameters, end heading in degrees and radius in miles, the command may be written:

MAKE TURN (ENDHEAD 150°, RADIUS 0.5 MIL)

or MAKE TURN (150, 0.5)

3. The time duration units must be a unit defined in the vocabulary list.

4. The "next action label" gives the label of the action command to do next. If there is no label specified, the same command is repeated after the wait time. If the "next action label" is NEXT, the next sequential non-test command is executed. This saves the need for labels on all commands.

5. UNLESS or test commands may not have a label and thus may never be referenced. They are modifying commands only.

6. The "action command label" and "next action label" are any user-written labels of up to 18 letters. The label must be written the same way each time (excluding blanks).

TABLE A-4. ACTION SYNTAX

Type 1 "order" commands:

[ "action command label" ] : "command description" [ numerical ] [ quantity ] [ "units" ]

("description" parameter "unit")

repeat for as many

← parameters as needed →

separated by commas

[ , time duration [ "units" ] ] [ ; "next action label" ] .

Type 2 "test" commands

UNLESS "command description"



[ numerical ] [ quantity ] [ "units" ] "next action label".

7. No description (command description, units, label) may include anything but letters.
8. No description (unit, label, command) may start with the letters UNLESS.
9. Action commands may be typed in free format because blanks and carriage returns are ignored.
10. No continuation characters are needed for continuing a command on the next line.

Examples of several commands (sentences) allowed with this syntax are:

LEG 1: MAKE TURN TYPE 2 (ENDHEADING 15; RADIUS 0.2 MI), 15 MINS; START  
LEG 2.

UNLESS SPEED < 5 KNOTS; NEXT.

RESET PROBLEM.

c. Action Command Description. This section presents an incomplete list of orders and tests used by action commands to illustrate their application. The exact phrases used to describe the order or test may be changed according to user preference. Additional orders and tests are easily added to the program structure.

Orders:

SET FIX FREQUENCY TO  $\underline{n}$  MINS

LORAN FIX EVERY  $\underline{n}$  MINS

RIGHT RUDDER  $\underline{x}^{\circ}$

LEFT RUDDER  $\underline{x}^{\circ}$

COME TO HEADING  $\underline{x}^{\circ}$

LOAD HISTOGRAM/CHART/COUNTER  $\underline{n}$

RESET PROBLEM

TURN  $\left\{ \begin{array}{l} \text{RDF} \\ \text{RADAR} \end{array} \right\}$  ON/OFF

STEADY ON COURSE

RUDDER MIDSHIP

UPDATE SPEED ESTIMATE

COME TO PRESENT HEADING  $\pm \underline{x}^{\circ}$

COME TO HEADING FOR COURSE  $\underline{x}^{\circ}$

CHANGE RUDDER  $\pm \underline{x}^{\circ}$

AHEAD FULL/ $\frac{1}{2}$ /

STEADY ON AID  $\underline{n}$

STEADY ON RANGE  $\underline{n}$

CHANGE THROTTLE  $\pm \underline{x}$

SIGHT ASTERN  
 LOOK IN DIRECTION  $\underline{x}^{\circ}$   
 CHANGE DR CONFIDENCE TO  $\underline{x}$   
 CHANGE  $\left\{ \begin{array}{l} \text{LORAN} \\ \text{RADAR} \\ \text{etc} \end{array} \right\}$  CONFIDENCE TO  $\underline{x}$   
 AUTOPILOT ON/OFF

Test:

UNLESS OFF TRACK  
 UNLESS OFF TRACK SB  
 UNLESS OFF TRACK PORT  
 UNLESS OUTSIDE SB/PORT BOUNDARY  
 UNLESS COMPASS HEADING  
 UNLESS SPEED  
 UNLESS EST COURSE  
 UNLESS ALONG TRACK WIND/CURRENT EFFECT  
 UNLESS ACROSS TRACK WIND/CURRENT EFFECT  
 UNLESS RANGE ALIGNED  
 UNLESS RANGE LINE SB/PORT  
 UNLESS CROSS TRACK VELOCITY  
 UNLESS EST LATITUDE  
 UNLESS EST LONGITUDE

## A.7 NAVIGATING AND STEERING MODEL - FUNCTIONAL FLOW AND DESCRIPTIVE EXPLANATION

### A.7.1 Introduction

Much has already been said about the decisions and criteria that shaped the development and structure of this program, and about many of its features and capabilities. Several of the program functions have also been described in detail. What is needed at this point is, first, to step back and view the program as a whole, and then to examine the various pieces and see how they interact and tie together.

FIGURE A-11 is a simplified function diagram of the entire navigating and steering program. Each box gives a function that is performed by the program, and the description to the left of each box describes the function. The primary purpose of this diagram is to distinguish between the realms of the main functions. The arrow that circles around to the left indicates that the various functions are repeated each time the simulated time is advanced.

FIGURE A-12 is a more detailed diagram of the program. The arrows indicate direction of the program flow. The boxes indicate functions. In this case, a function is not only a separate, real world process, but also a separate program piece, or module.

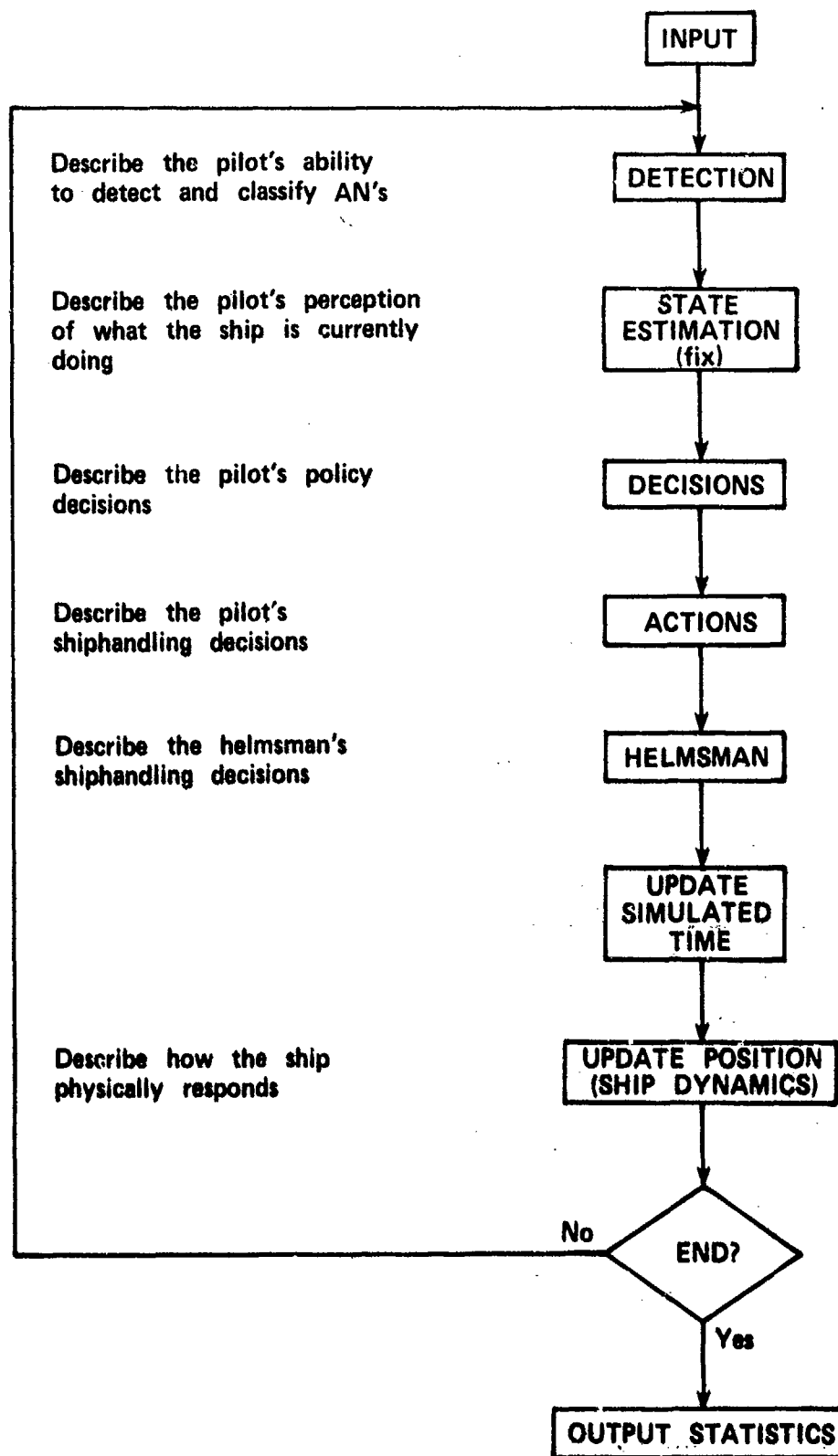


FIGURE A-11. NAVIGATING AND STEERING PROGRAM SIMPLIFIED FUNCTION DIAGRAM

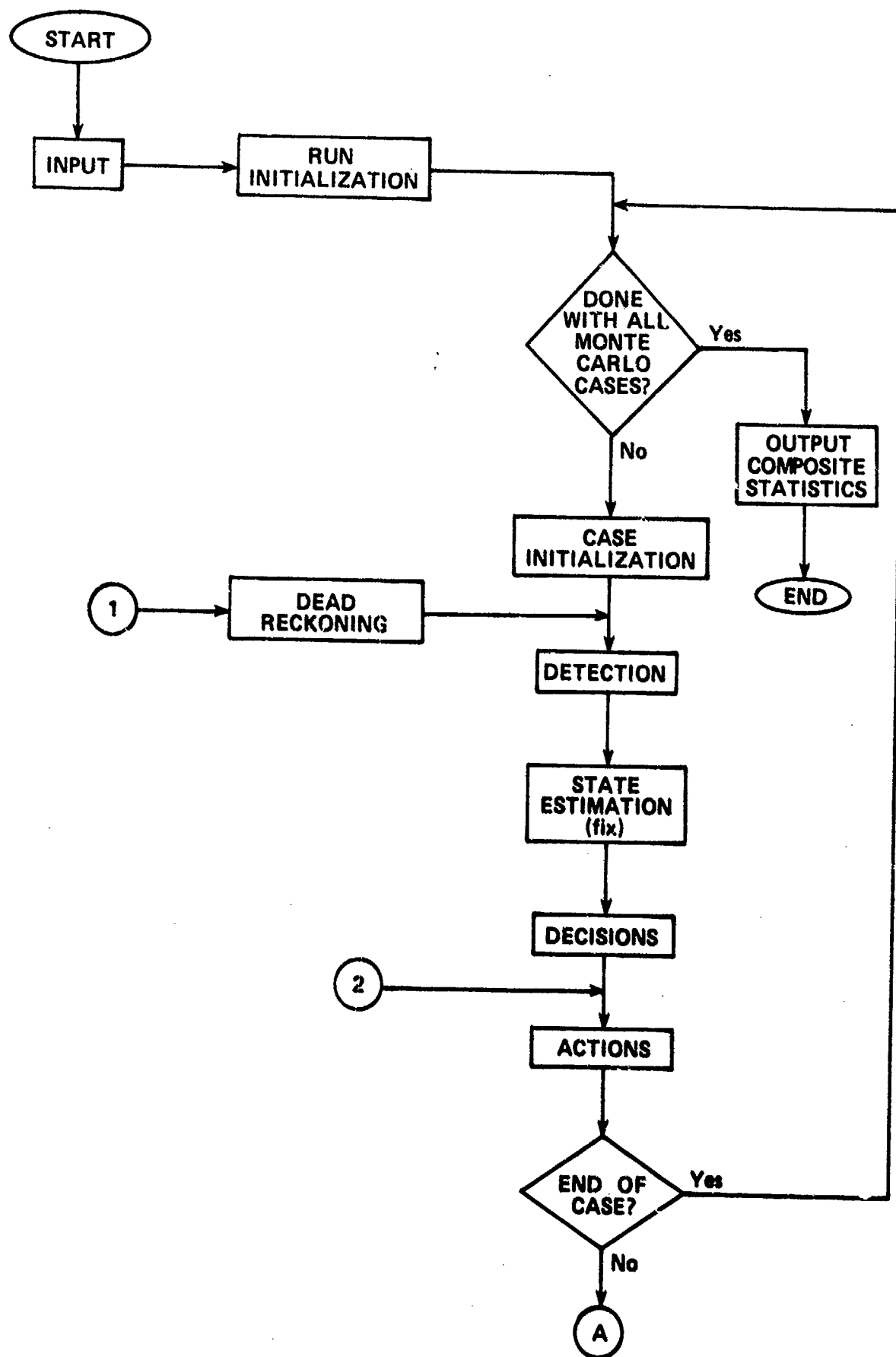


FIGURE A-12. NAVIGATING AND STEERING PROGRAM DETAILED FLOW DIAGRAM (SHEET 1 of 2)



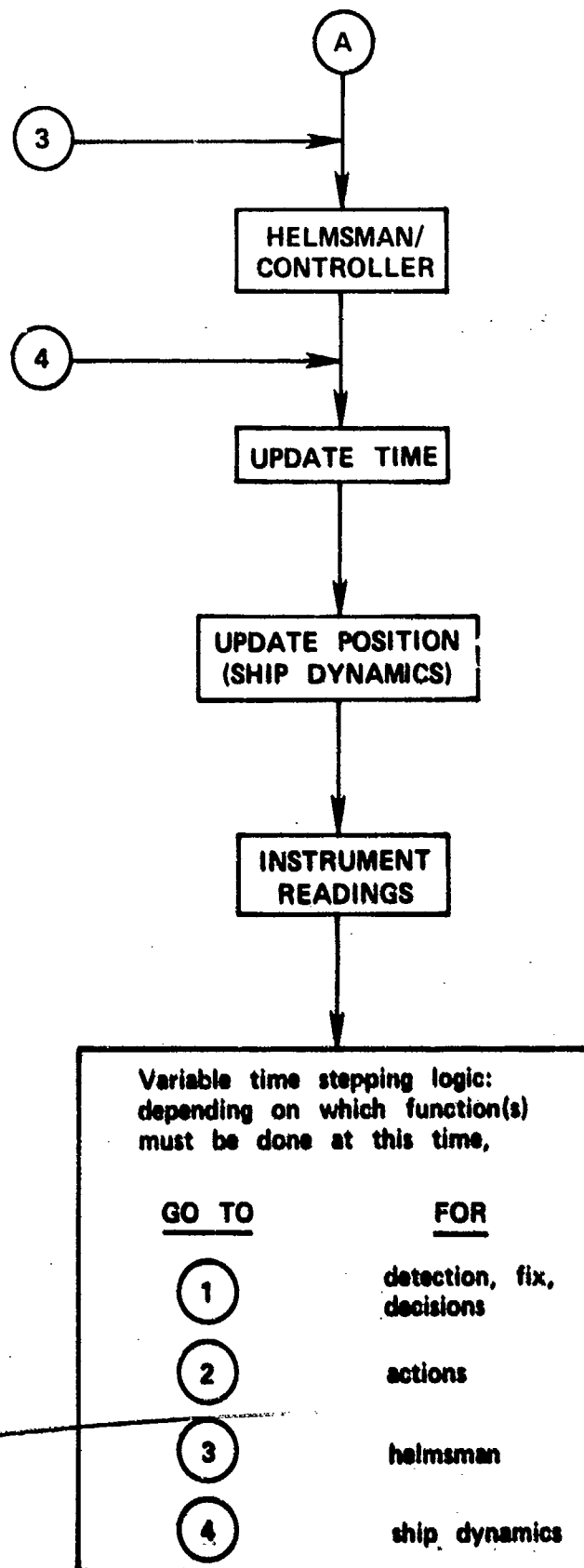


FIGURE A-12. NAVIGATING AND STEERING PROGRAM DETAILED FLOW DIAGRAM  
(SHEET 2 of 2)

The careful distinction between the various functions in the program is made so that any module can be replaced by another module which performs the same function and the rest of the program would not be affected. For example, a definite range law detection module could be replaced by a probabilistic detection module and none of the rest of the program would have to be changed.

Each function block in FIGURE A-12 will be described in a separate section that follows. The functions contain the major logic of the program and the names agree with the names on the flow diagram. Some functions handle a variety of logic, and thus include several subfunctions. These subfunctions are described immediately following the function description. Each function and subfunction section will include a description of the function or subfunction, the input and output parameters used, and any details that may be of interest.

#### A.7.2 List of Functions in Chronological Order as They Appear in the Navigating and Steering Model

<u>Function</u>	<u>Subfunction</u>	<u>Section</u>
Input		A.7.3
Run Initialization		A.7.4
Case Initialization		A.7.5
Dead Reckoning		A.7.6
	Retention	A.7.7
Detection		A.7.8
	Observation	A.7.9
	Perseverance	A.7.10
	Alignment	A.7.11
State Estimation Fix)		A.7.12
	Electronic Fixing	A.7.13
	Fix Location from Observations	A.7.14
	Fix Confidence	A.7.15
	Wind and Current Estimate	A.7.16
Decision		A.7.17
Action		A.7.18
Helmsman/Controller		A.7.19
Update Time		A.7.20
Update Position (ship dynamics)		A.7.21
Instrument Readings		A.7.22
Output Composite Statistics		A.7.23

### A.7.3 Input Function

Description: All input required by the program to fully model a given scenario is ready from libraries and/or keyboard entries. The data, error functions, distributions, and English-like tactical logic are interpreted and checked for errors. All errors are flagged for the user to correct. The corrected data are then stored in the representation needed for the actual simulation. The data may also be saved in the library for future use.

#### Parameters: Input

Miscellaneous data (timing information, number of cases to run, type of output desired, etc)

Starting conditions (initial ship position, heading, speed, and distribution on them)

AN positions (chart location and distribution on actual location)

AN characteristics (type of aid, color, height, intensity, classification number)

Track (description of each leg of track, including length, radius, heading, desired speed, traffic density, frequency of updating fix, current, channel width, etc)

Decision logic (set of decision commands to be used for this scenario)

Action logic (set of action commands to be used for this scenario)

Fix data (number of boxes in grid, box sizes, conditions under which bearing observations become independent, algorithm for determining which buoys to use in fix, algorithms for determining how often to take fixes under various conditions, etc)

Ship type (height of pilot, height of radar mast, ship dynamics coefficients, etc)

Instruments and pilot behavior (errors and correlation times on gyro compass and speed log or rpm, distributions on pilot's responses, etc)

Sensor table (what sensors are aboard, algorithms for their usage, and pilot's confidence in them)

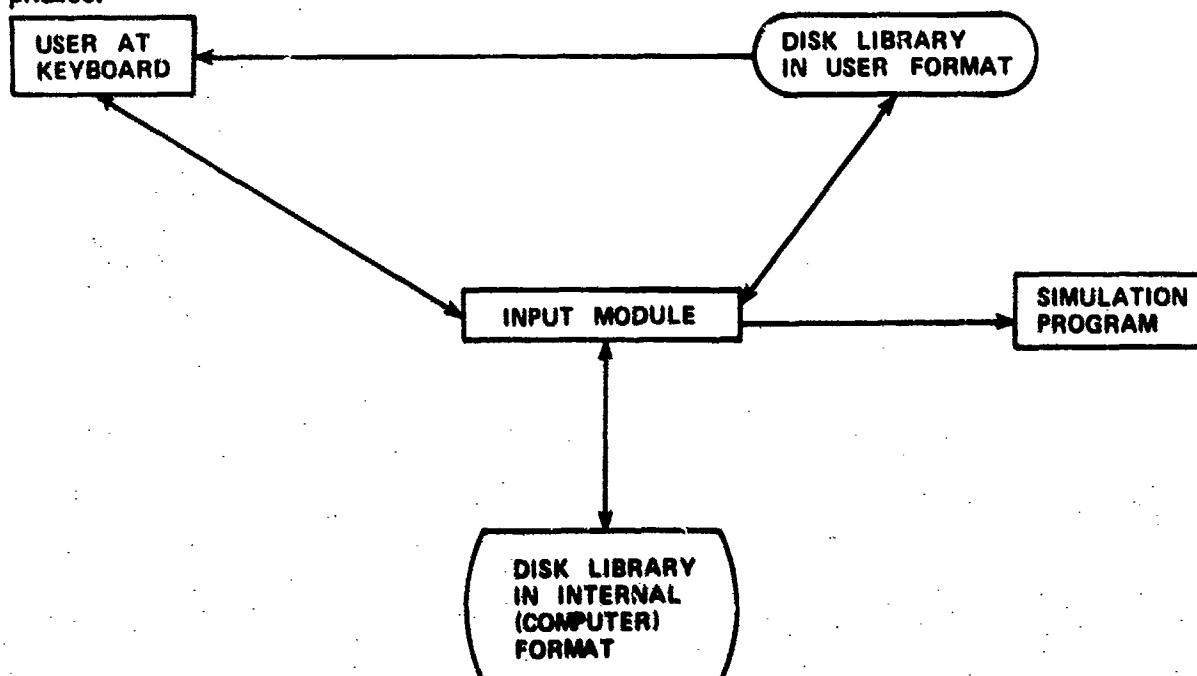
Environment/weather data (visibility, wind, tide, wave height, background luminous intensity, radar clutter, acoustic loss, etc)

Statistics desired (output charts/histograms/plots desired, labels)

#### Details:

The input data are divided into sections according to functions (i.e., all ships type data is in one section). The input module accepts one section of data at a time and will query the user for it. The user has several choices. He may decide

to examine one of several alternative sections on the disk library. These data are in user format and include descriptive headings. The user may choose to edit or change parts of these data and then accept it, or he may decide to accept it as is. Or he may decide to enter entirely new data for this section from the keyboard by typing in each piece of data called for by the description. If the user enters a new section of data or edits one from the library, the input module will interpret and check the data, ask for corrections, and then store the data in internal format for use by the simulation program. The data section may also be stored on the library both in user format (for later examination and editing) and in internal format (for later direct use by the program). If the user had chosen to use a section of data from the library without any changes, the input module would simply use the data already in internal format and thus avoid the interpretation and error checking phases.



The user formatted library file is designed to make use of the editing capability of the particular computer used.

The input module includes two syntax translators which translate the English-like decision and action syntax into computer instructions. See the sections on the decision and action function for a description of the syntax.

#### A.7.4 Run Initialization Function

**Description:** Initializes conditions and picks values from distributions for variables which will remain constant throughout all Monte Carlo cases. This sets up the model or scenario.

**Parameters:** Input

AN chart position and error distributions

Tide statistics

Wind and current statistics

Propagation statistics  
Equipment error distributions  
Ship dynamics coefficients

Output

Actual AN positions for this run  
Actual ride, wind, current, visibility, etc  
Equipment failures

Details:

Depending on the model or scenario, it may be desirable to change some of the parameters listed above on a case by case basis instead of having them remain constant throughout the run. This is accomplished simply by indicating in the input which parameters are initialized once for the run and which are initialized with a new random value for each case (see next section).

A.7.5 Case Initialization Function

Description: Initializes conditions for the start of each Monte Carlo case. Pick values from distributions for variables which vary from case to case.

Parameters: Input

Ship's starting position, heading, speed, and distributions  
Ship state statistics

Output

Perceived ship state vector (ship's estimated position, heading, speed, wind and current effect)  
Initial actual ship state

Details:

Depending on the model or scenario, it may be desirable to change some of the parameters listed in the previous section on a case by case basis, or to keep some of the parameters listed above constant throughout the entire run. This is accomplished simply by indicating in the input which parameters are initialized once for the run and which are initialized with a new random value for each case.

A.7.6 Dead Reckoning Function

Description: As time passes, the pilot updates his estimate of where he is, based on his estimate of the wind and current effect, and the compass and speed indicator readings. At the same time, his confidence in his estimated position is lessened.

Parameters: Input

Perceived wind and current effects and sigmas  
Gyro compass reading and perceived sigma  
Speed indication reading and perceived sigma  
Time since last fix  
Actual course and ground speed  
Probability grid (for estimated position)  
Pilot's confidence in DR

Output

Updated probability grid (for estimated position)

Details:

The problem of estimating ship position and position uncertainty is modeled, assuming independent Gaussian distributions on speed and course since the previous position fix, and using a discrete grid representation of the 2-dimensional position fix uncertainty.

True speed and course need not be the same as pilot's perceived speed and course, nor need the variances be those the pilot estimates. This allows for biases, as well as greater or lesser confidence on the part of the pilot.

From a starting position, it is necessary to determine the probability of arriving within an elemental area about an end position. No assumptions are made on the form of the estimated position uncertainty density function other than that it should approach uniform as the distance from  $X_0, Y_0$  (true position at previous time  $t_0$ ) increases. The resulting DR grid gives the probability of arriving at each cell in the grid at time  $t_1$ . This probability is the sum over all cells about  $X_0, Y_0$  of the probability of starting at that cell multiplied by the probability of moving to the new cell.

A.7.7 Retention Subfunction

Description: Even with perfect dead reckoning, there is a decay in fix confidence with passing time. This algorithm will cause the grid to decay toward a uniform distribution.

Parameters: Input

Grid resulting from dead reckoning  
Time of previous fix  
Current time  
Retention time constant

### Output

Updated DR grid reflecting decay in confidence

### Details:

Handled in conjunction with determining the probability of arriving within a given cell at a given time from the given starting position.

## A.7.8 Detection Function

Description: The pilot looks for each specific AN using one or more sensors (visual, radar, etc). The detection threshold is a function of physical parameters and human parameters.

### Parameters: Input

Visibility (or propagation loss)  
Background (or noise)  
Other specific interferences  
AN intensity or reflectivity (or apparent signal)  
Sensor in use (or array gain)  
Observation capability (or recognition index)  
Alertment gain (expectation)  
Actual range, bearing to each aid

### Output

Which ANs detected

### Details:

Duntley's Nomogram for daytime detection by sun reflection and Allard's equation for detection of lighted aids should account for all but interference and alertment. Interferences need to be dealt with on a harbor and traffic specific basis. Alertment gain depends on previous observations in this harbor transit and current confidence in fix.

Separate algorithms are used for each type of detection to be modeled: visual (lighted or unlighted), radar, definite range law, etc.

## A.7.9 Observation Subfunction

Description: The pilot observes each individual AN and a number is obtained for the current value of observed range and bearing.

### Parameters: Input

Whether detection was made

True ranges and bearings

Observation a priori distribution in absence of alignment and perseverance

Previous value of observed parameter

Perseverance correction and independence measure

Alignment correlations and independence measures

Output

Perceived sigmas on all range and bearing observations

Observed range to each AN

Observed bearing to each AN

Actual sigmas on all range and bearing observations

Details:

The observed range and bearing to each AN is determined by sampling values from range and bearing error distribution functions (based on the actual range and bearing). This is the a priori observation in the absence of perseverance and alignment. The effects of perseverance and alignment (see next two sections) will modify the a priori observations to give the actual range and bearing observations used in fix and decision-making.

A.7.10 Perseverance Subfunction

Description: When a specific observation of a parameter is made, there is a tendency for subsequent observations to be at or near the previous observation.

Parameters: Input

Time since last observation

Change in parameter value since last observation

Time perseverance

Parameter perseverance

Output

Correlation coefficient

Independent measure

Details:

The correlation coefficient and the independence measure are calculated for later use in observation and fix location.



#### A.7.11 Alignment Subfunction

Description: When the relative bearings of two ANs become the same, the alignment allows a much more accurate bearing judgment for fix purposes than would result from both aids independently.

Parameters: Input

Height of pilot eye (sensor)  
Height of AN (center of detectable area)  
Geometrical bearing difference between ANs

Output

Correlation coefficients  
Independence measures

Details:

The correlation coefficients and independence measures are calculated for each AN as they relate to the next aid in the direction of increasing bearing and decreasing bearing for later use in observation.

#### A.7.12 State Estimation (Fix) Function

Description: The pilot makes visual and radar fixes and combines these with his dead reckoning estimates and electronic fixes to obtain his best estimates of present position. A fix confidence is also calculated for decision-making purposes. From present and previous position estimates, the pilot estimates wind and current effect, course, and speed over ground.

Parameters: Input

Probability grid from dead reckoning  
Observed visual range and bearing to each detected AN  
Observed radar range and bearing to each detected AN  
Observation statistical distributions (perceived)  
Risk of error in position estimate  
Actual ship and AN positions

Output

Updated fix probability grid  
Estimated position  
Across track fix confidence  
Along track fix confidence  
Estimated wind and current effect and sigma

Estimated course

Estimated speed over ground

Details: See subfunctions and Section A.5 (Fix Technique).

#### A.7.13 Electronic Fixing Subfunction

Description: A LORAN or other electronic fix would be made at frequencies set by the pilot (input or action commands) depending on the scenario. This new fix would be used in conjunction with dead reckoning and other fixes (e.g., visual) in the estimate of position.

Parameters: Input

Frequency of electronic fixes

Probability grid (for estimated position)

Characteristics of particular electronic fix method and distributions

Pilot's confidence in each method

Output

Updated probability grid (for estimated position)

Details:

The probability of being in each box of the DR updated grid according to the electronic fix is determined from the characteristics of the method. These numbers are then multiplied by the number (probability) already in the box from DR updating and the results normalized and used as the new grid.

There is no restriction to the number of types of electronic fixes that may be made (including shore-based traffic controller messages). They are all handled in the same manner and are all combined to give the final estimated position.

The pilot may attach more importance to radar observations than LORAN, or to visual observations than radar. This type of behavior is modeled by "weighting" the information received from each type of fix according to pilot's preference.

#### A.7.14 Fix Location from Observations Subfunction

Description: The previous dead reckoning result, any electronic fixes, and the current observations (visual, radar) are combined to yield a new best estimate of present location.

Parameters: Input

Probability grid resulting from dead reckoning and electronic fixing

Observed values for range and bearing to each AN

Actual position of ANs and own ship

Pilot self confidence

Independence measures from perseverance and alignment

A priori distribution as used in observation

Pilot's confidence in various types of observation (e.g., radar, floating aids)

Output

Ship's present estimated position

Details:

For each box in the grid, calculate the actual value of the parameter which would be consistent with present ownship location being in the box. Then determine the a posteriori probability that the box position was the actual location, given the observations. Correct this result by the independence measure for the observation. Multiply this result by the number that is already in the grid box and repeat for all boxes and all observations. The grid is then normalized. This is the likelihood function. The maximum likelihood estimate is the largest mode of the likelihood function. (See Section IV on Fix Techniques.)

Note, even if no observations or electronic fixes are made, the best estimate of present position is calculated from the grid as above. This gives the dead reckoned position.

The pilot has certain confidence in his dead reckoning, in the various electronic aids, and in various types of observations (e.g., radar vs visual, fixed vs floating aids). The resulting fix reflects his particular areas of confidence or distrust because all types of information which go into making the fix (i.e., which enter the grid) are "weighted" according to the pilot's preferences.

**A.7.15 Fix Confidence Subfunction**

**Description:** The pilot's confidence in his estimated position is calculated in both the along track and across track directions. An along-across track correlation term is also calculated.

**Parameters: Input**

Probability grid from fix

Desired track direction

Perceived fix location

**Output**

Along track position variance

Across track position variance

Along-across track correlation term

Details:

The variances are calculated based on the spread of probabilities in the grid according to the direction of the desired track.

**A.7.16 Wind and Current Estimate Subfunction**

Description: From present and previous position estimates, the pilot estimates the wind and current effect, and his course and speed over ground.

Parameters: Input

Probability grid  
Previous position estimate  
Time since last estimate  
Gyro compass heading and sigma  
Speed indication reading and sigma

Output

Estimated wind and current effect and estimated sigmas  
Estimated course  
Estimated speed over ground

**A.7.17 Decision Function**

Description: This describes the pilot's policy decisions. It models the decision-making logic that is used in determining what action to take under any of the various conditions that may arise.

Parameters: Input

Decision commands translated into a matrix of numbers  
Decision block to start with  
Values for testing: AN detection/classification status;  
AN observed range and bearing;  
Estimated ship position, heading, course, speed;  
Confidence in fix;  
Visibility;  
Traffic density;  
Time;  
Time on leg;  
Cross track position; etc

### Output

Action block to do next

Statistics

### Details:

All IF/AND/OR commands are tested in order starting with the block specified until one is satisfied. This gives the action command block to execute next (if there is a new action block) and the decision block to start with at the next time step. If a new action block is specified, the time for a new action is set to the present time. If not, the action command execution is not interrupted.

See section on Decision for a complete description of the decision language (syntax and commands).

## A.7.18 Action Function

Description: This describes the pilot's ship-handling decisions. It models the decision-making logic that is used in determining how to carry out an action and the orders necessary to ensure that the action is carried out.

### Parameters: Input

Action commands translated into a matrix of numbers

Action command to start next

Time to start next action command

Values for testing: Edge of track limits;

Estimated position, speed, heading, course;

Time;

Estimated wind and current effect;

Desired course and speed for this leg;

Cross track velocity, etc

### Output

Time to start next action command

Action command to start next

Program values that have been changed: frequency of taking fixes, ordered heading, ordered turn rate, ordered rudder angle, ordered throttle, sensors turned on/off, order to reset problems, order to look astern, confidence in dead reckoning, etc

Statistics

### Details:

If it is time to execute the next action command, the program starts with the command specified and examines the commands in order until one is found where

no UNLESSes are satisfied (true). That command is executed. If that command has no time duration, the program executes the next appropriate command and the next, until one is found with a time duration. That time duration represents the next time that any action commands need to be executed (unless conditions change and the decision logic indicates a new action block, in which case the new action will take precedence over the present action and start immediately).

Output from the action commands may give ordered heading, ordered throttle, specification for how often to take fixes, etc.

See section of actions for a complete description of the action language (syntax and commands).

#### A.7.19 Helmsman/Controller Function

Description: This models the helmsman's or ship controller's determination of proper rudder angle to give the ordered heading in the ordered time.

Parameters: Input

Ordered heading  
Present compass heading  
Ordered time for completion  
Knowledge of the ship (ship dynamics coefficients)  
Present rudder position  
Present turn rate

Output

Ordered rudder angle  
Length of time for rudder order

Details:

Because the program is modular, the controller function may be done by a human helmsman or by an autopilot. The autopilot may be turned on and off by action commands. Also, the pilot may specify rudder orders himself in the action commands (in which case the helmsman function is skipped), or he may order headings. In that case, the helmsman or autopilot will calculate the proper rudder angle to give the ordered heading in the time allowed or at the range indicated by the action command. See FIGURES A-13 and A-14.

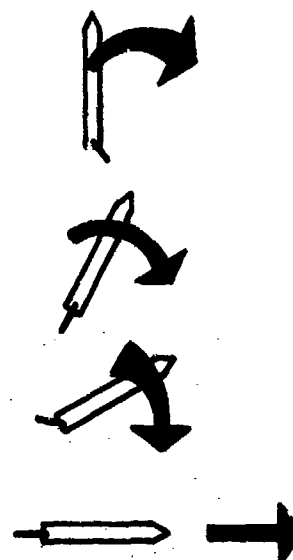
#### A.7.20 Update Time Function

Description: Determine the time step based on the fix frequency, planned maneuvers, ranges to ANs, and ship dynamics integration time requirements.

Parameters: Input

**GOAL: ACHIEVE COURSE CHANGE IN MINIMUM (OR SPECIFIED)  
TIME WITHOUT GENERATING EXCESSIVE TURN RATE  
OR OVERSHOOT**

- PHASE I** PICKS RUDDER TO  
ACHIEVE DESIRED  
TURN RATE & TURN  
DURATION
- PHASE II** RETURNS RUDDER TO  
MIDSHIPS TO CONTINUE  
SWING
- PHASE III** APPLIES BACKING  
RUDDER TO CHECK  
SWING
- PHASE IV** MIDSHIPS ON COURSE  
NO TURN RATE



**REQUIREMENTS:**

- A. PREDICT RESULTS OF APPLICATION OF RUDDER**
- B. ABILITY TO CORRECT FOR INITIAL MISJUDGMENT**
- C. VARIABILITY IN TIME TO ACHIEVE ORDERED COURSE**

**FIGURE A-13. HELMSMAN'S STEERING PROCESS**

## **GIVEN NEW ORDERED COURSE**

- I. FIND A RUDDER ANGLE THAT WILL MINIMIZE THE SUM OF TURN COMPLETION TIME PLUS A MULTIPLE OF TURN RATE

FAST TIME PROJECT EFFECTS OF ALTERNATE RUDDERS

SELECT BEST

APPLY RUDDER

- II. WHEN THRESHOLD TURN RATE ACHIEVED, ORDER MIDSHIPS

IF TURN RATE NOT ACHIEVED AFTER PREDICTED TIME,  
RETURN TO I

IF TURN RATE DECAYS TOO RAPIDLY, RETURN TO I

- III. WHEN APPROACHING COURSE, DETERMINE BACKING RUDDER TO JUST STOP SWING ON DESIRED COURSE

APPLY BACKING RUDDER

- IV. WHEN ON COURSE WITH ZERO TURN RATE, RETURN TO MIDSHIPS.

**FIGURE A-14. HELMSMAN SUBROUTINE**



Time till next fix  
Time till next maneuver  
Maximum time step allowed  
Time till new rudder angle required  
Time till must update ship because of integration time

Output

Time step ( $\Delta T$ )

Details:

The program has a truly variable time step. Each function is updated only as often as is required for accurate modeling of the process. Not all functions are updated at the same frequencies. For example, the ship state might be updated every 3 seconds (because a short time step is necessary to get realistic ship tracks from the ship dynamics equations), while the fix might be updated only every 60 seconds (because that is how often a pilot would or could actually assess new information in the given situation).

The timing control is a nested-loop process, whereby the simulation time may be advanced and an inner loop executed without executing any of the outer loops at that point in time. However, at the time that any loop is executed, all loops inside that loop must also be executed. The nested time loops are as shown in FIGURE A-15.

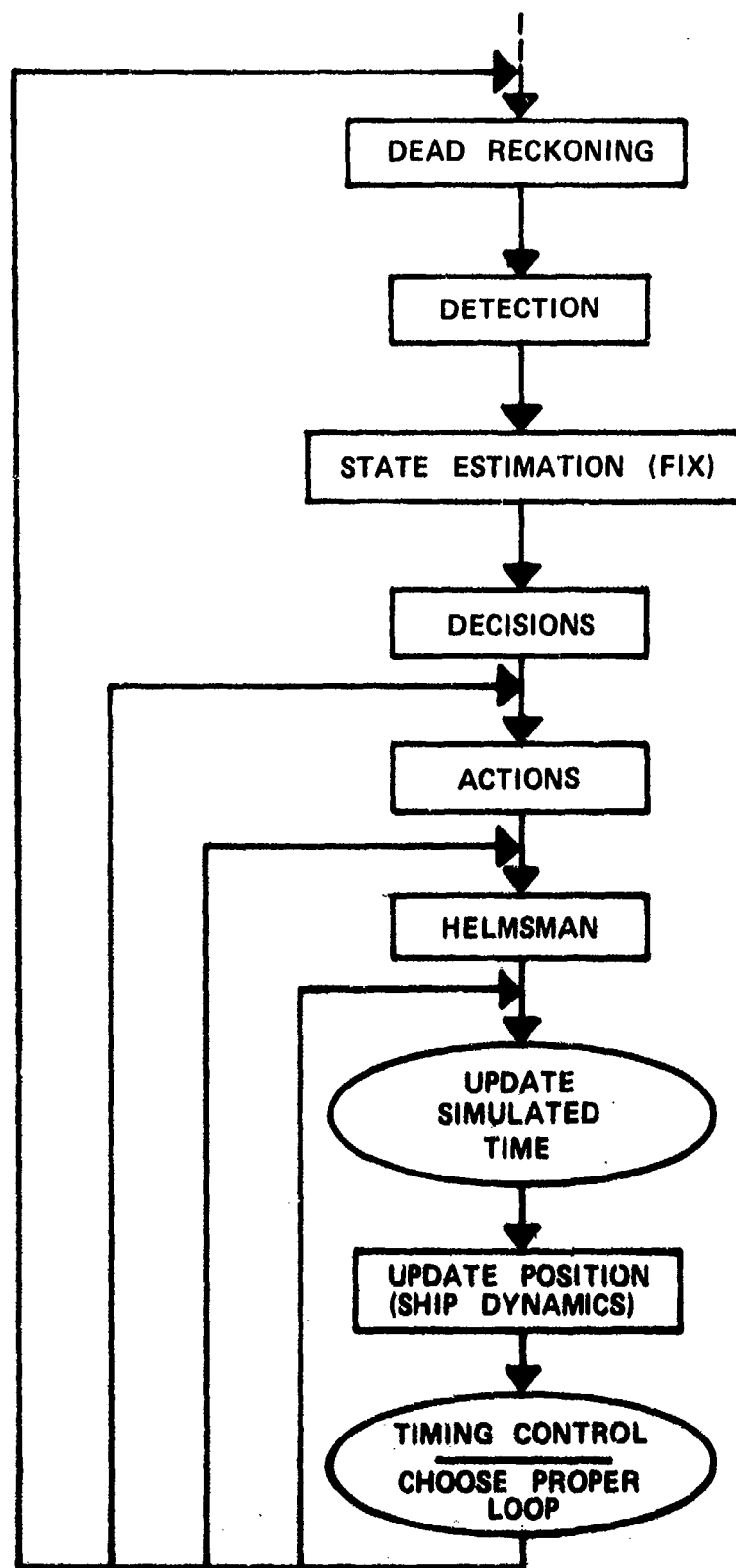
The frequency of doing the dead reckoning, detection, fix, and decision functions is controlled by action commands. The logic of both the actions (maneuvers) and helmsman routines generates its own appropriate time step. Thus, the time-stepping of various functions changes as the scenario progresses, in response to changing conditions.

**A.7.21 Update Position (Ship Dynamics) Function**

Description: Update ship's position to present simulated time based on ship type, wind and current.

Parameters: Input

$\Delta T$  (time step)  
Old heading  
Old speed  
Old throttle setting  
Old turn rate  
Old rudder angle  
Old position  
Ordered rudder angle  
Ordered throttle



A-11

FIGURE A-15. NESTED TIME LOOPS

Ship dynamics coefficients for ship type  
Actual wind and current effect

Output

Present actual heading  
Present actual speed over water  
Present rudder angle  
Present turn rate  
Present position  
Present actual course  
Present actual speed over ground

Details:

A general ship dynamics algorithm is used, which will accept coefficients for any ship type.

**A.7.22 Instrument Readings Function**

Description: This models the compass and speed indicator readings at any time. Both electronic integration time and human perseverance (retention of previous readings) are considered.

Parameters: Input

Actual heading  
Actual water speed  
Actual gyro compass sigma  
Actual speed indication sigma  
 $\Delta T$  (time since last observation of compass or speed indicator)  
Speed/heading correlation time  
Previous speed/heading errors

Output

Estimated (or compass) heading  
Estimated (or speed meter) water speed  
Estimated speed/heading sigma

Details:

The estimated (or gyro compass) heading and estimated (or speed indication) water speed are calculated in the same manner. A random error from the appropriate distribution is added to the actual value to obtain the instrument reading. The present error is correlated with the previous error depending on the

time between readings and the heading/speed change. See description of subfunction perseverance.

#### A.7.23 Output Composite Statistics Function

Description: Output statistics for entire run (many Monte Carlo cases) as instructed by input. Output may consist of printed, plotted, or stored graphs, charts, tracks, logs of entry, etc.

Parameters: Input

Amount of detail desired on log of entry

Description of position plots (tracks) desired

Description of graphs, charts, histograms desired

Which output is to be printed, plotted, and/or saved on disk files for later use

Output

Print, plots, disk files

Details:

The sequential or "log of entry" output which describes each case on a time-by-time basis is collected for printing and/or saving as the run executes. Likewise, any values that must be saved or occurrences that must be noted are kept track of as they happen during each case. The information that is to be collected during each case and saved for later output is fully described by input, and may change from run to run.

When the program ends (all cases are run), the output module manipulates and develops the various data into the form specified by input (plots, graphs, charts, etc). It then prints, plots, displays, or saves this data.

#### A.8 GENERAL PROGRAM SUMMARY COMPUTER REQUIREMENTS, AND SIZE OF THE PRESENT DEMONSTRATION PROGRAM

The navigating and steering computer program is a simulation tool designed for rapid and detailed modeling of aid to navigation utility. While the program description has been largely concerned with evaluation of floating, fixed, and electronic ANs, it has, nevertheless, been carefully structured to have a much wider range of application.

To gain an appreciation of the navigating and steering program, it is helpful to consider it as a language rather than a program model. The compiled program has been designed to accept and process inputs describing the type and configuration of ANs under consideration, the piloting policy, the human decision-making process, and characteristics of the physical background. Thus, a simulation model is actually specified entirely through input statements.

The navigating and steering program has its own language and syntax to facilitate model creation, making it possible for the analyst to write or change the model directly without the services of a programmer. Using this program, the analyst has the direct

capability to write a model to address the specific situation to be examined and then to evaluate the performance of the ANs which are contained within the waterway.

#### A.8.1 Navigating and Steering Program Computer Requirements

The present demonstration program represents a positive indication of the success of our methodology and its substantial level of completeness illustrates the feasibility of developing the complete program. The following characteristics illustrate these points.

a. The current program consists of 2400 lines of FORTRAN source code and requires 55 pages of listing.

b. The main program resides in 28K of 16 bit words of core. Data files which support the program easily reside on one 1.2M word capacity disk. These currently represent 24K for the executable program and 16K for 1 input and 10 repetitions of output files. These of course are flexible and easily accommodated on disk storage. The program may be overlaid in any one of its three sections (input, simulation, and output), thereby further reducing core requirements.

c. The current computer is a DEC PDP 11/40 graphic system. The FORTRAN source code from this system has proved, in our experience, to be very portable to other scientific machines. This, along with the large popularity of DEC machines, gives confidence in the non-machine dependency of the program.

d. In addition to the main program the traffic model was developed as a separate program. This consists of 500 lines of FORTRAN source code. This program requires 16K of core and will therefore operate easily on the same machine as the main program.

Our projections of the future program when completed are as follows:

a. Program size is estimated to be approximately 40 percent of the eventual program. This size increase can be accommodated in a 32K machine through overlay techniques and at a cost of increasing run time. We anticipate that the final program will require 64K core and the support of two mass storage devices (disk) each consisting of 1.2M words.

b. Program run time is expected to be fairly long, requiring sequential batch mode processing in off prime time hours to reduce initial costs of developing summary output files.

Demonstrations at Eclectech Associates of the current program may be arranged, at the USCG's convenience.

## Appendix B

### MARINER'S REQUIREMENTS FOR, AND INFORMATION OBTAINED FROM AN

B.1	GENERAL REQUIREMENTS FOR USERS OF AIDS TO NAVIGATION	B-2
B.1.1	Scenario One - Coastwise Pilot Waters	B-2
B.1.2	Scenario Two - Harbor Approach	B-16
B.1.3	Scenario Three, Four, Five - Outer Harbor Approach, Inner Harbor Channel, and River	B-22
B.2	AID TO NAVIGATION INFORMATION REQUIREMENTS	B-28
B.2.1	Along Track Position Estimate	B-28
B.2.2	Cross Track Estimate	B-28
B.2.3	Course Made Good Estimate	B-29
B.2.4	Speed Made Good Estimate	B-29
B.2.5	Wind Effects Estimate	B-29
B.2.6	Current Effects Estimate	B-30
B.2.7	Bank Bottom Effects Estimate	B-30
B.2.8	Ship Response to Helm Orders Estimate	B-30
B.2.9	Response to Traffic Problems	B-31
B.2.10	Navigating the Ship through Decisions and Actions	B-31
B.3	MODIFYING NAVIGATIONAL TASKS FOR ENVIRONMENTAL EFFECTS	B-32
B.3.1	Effects of Darkness	B-32
B.3.2	Effects of Rain, Snow, and Fog	B-33
B.4	INFLUENCE OF AID TO NAVIGATION PLACEMENT ON THE NAVIGATION PROCESS	B-33

## INTRODUCTION

This appendix and Appendix D discuss the manner in which pilots and ships' officers view aid to navigation (AN) information provided by various ANs and the manner in which they actually use these ANs in navigating pilot and coastal waters. These data represent a sampling of our methodology. As such we have attempted to take a position on the questions "What does a mariner require?" and "What do aids provide?" The basic answer is that this issue is very complex as a function of its multivariable nature and therefore the questions require specificity. The following data illustrate the method we have adopted to gain this degree of specifying geographic, user, and AN details from which an analysis can be conducted. Essentially our method, as applied in Phase I, has been to review actual at-sea or simulator data as is exemplified in this section and then model a specific set of conditions. We have avoided producing general conclusions at this time; instead we have concentrated on those areas where we have data. This, we hope will illustrate our approach to Phase II.

### B.1 GENERAL REQUIREMENTS FOR USERS OF AIDS TO NAVIGATION

Navigational methods used by seagoing vessels depend on the proximity of the vessels to hazards to navigation and on the type and accuracy of the fix desired. The following paragraphs describe navigational methods in coastal and piloting waters using short-range ANs, as observed at sea and recorded in data bases resident at Eclectech Associates (references 26 and 27 and Appendix C).

On the open sea where navigable waters extend for hundreds of miles, fix accuracies within a 10-mile radius of a vessel's actual position are at times acceptable, especially when weather conditions hinder celestial and electronic navigation. Course changes are made at intervals of 1 to 12 hours. Navigating in coastal and piloting waters demands greater precision both in obtaining fixes and in course control. Course or rudder orders may be given at a frequency of several per minute up to several minutes or even hours apart. To examine the various navigational methods that use short-range ANs, we developed five scenarios to compare and contrast navigation methods based on actual data. These scenarios include:

- Scenario One, Coastwise Pilot Waters
- Scenario Two, Harbor Approach
- Scenario Three, Outer Harbor Approach
- Scenario Four, Inner Harbor Channels
- Scenario Five, River Systems

#### B.1.1 Scenario One -- Coastwise Pilot Waters

Scenario One includes coastwise pilot waters where dangers exist at distances between 5 and 10 miles. FIGURE B-1 shows a typical coastwise area along the Florida Keys. Interview data suggest that ships' officers traversing these waters require navigational accuracies of 0.25 to 1.5 nautical miles to avoid hazards and maintain a track away from traffic lanes in the opposite direction. In these waters, the navigator can rely on the following aids to navigation: LORAN, lighthouses, buoys, beacons, directional radio

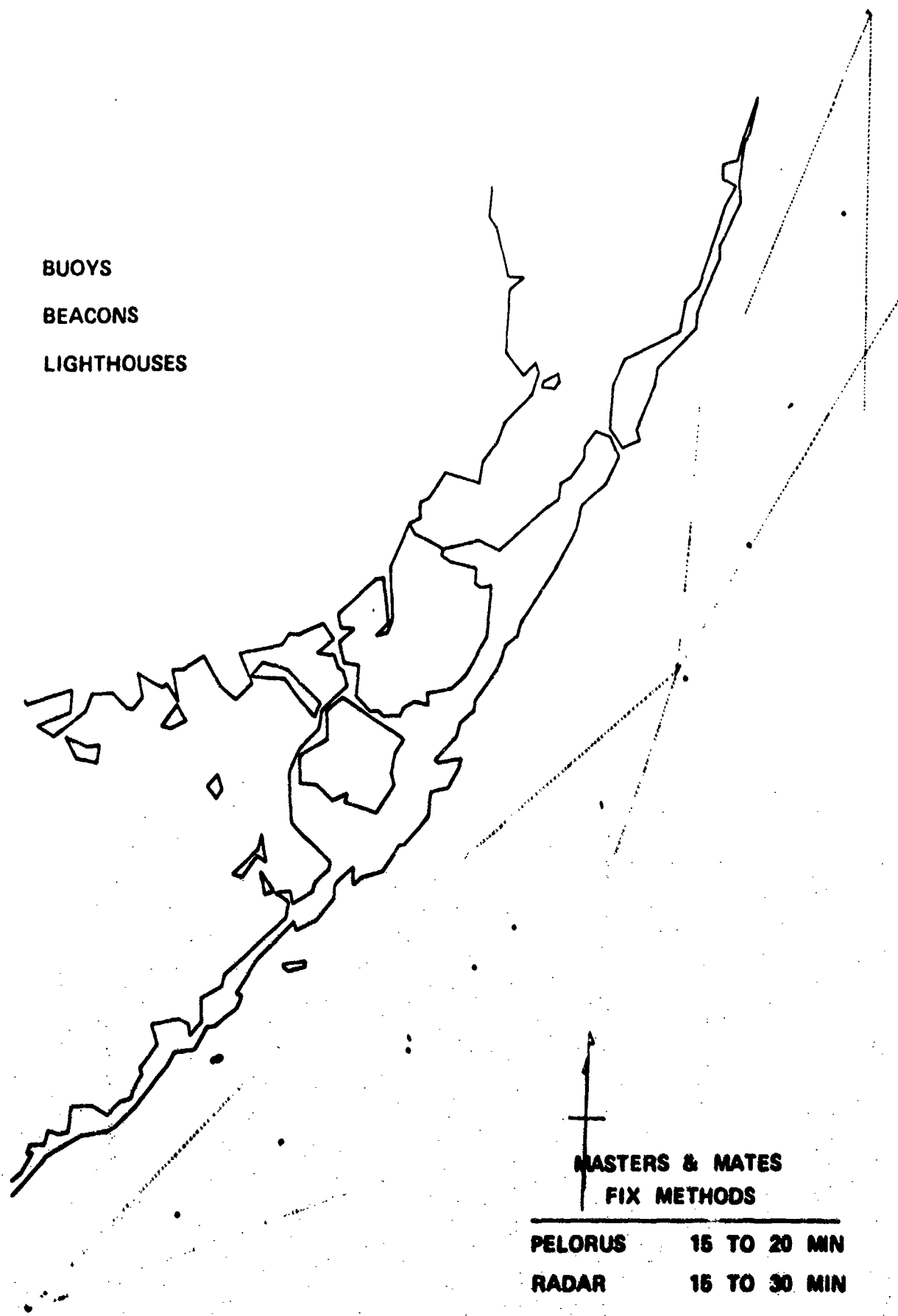


FIGURE B-1. SCENARIO ONE, COASTWISE PILOT WATERS



beacons, and RACON. Piloting methods using LORAN, pelorus, and radar provide a quick and accurate fix allowing more time for collision avoidance under heavy traffic conditions. To examine Scenario One conditions, we studied the data base described in reference 24. FIGURE B-2 gives an example of the data obtained during the run from the Florida Keys to New Orleans. Using the first line in FIGURE B-2, the data file can be read as follows:

36, Block file  
438, Julian date  
1607, Time task started  
15, task duration in seconds  
1, mate code number (first mate)  
14, task code number (one of 60 behavior codes)  
Radar 1 range, English description of the task.

In brief, the data file says that the first mate took a range and bearing from the 1-cm radar at 1607 hours; the task lasted 15 seconds.

Analysts spent many hours examining these data for patterns and trends for inclusion in the development of the model. FIGURE B-3 is an example of a condensed analysis of a specific navigation task analysis conducted on the data base for this study. Task frequencies are low indicating, in effect, that the bridge navigation workload in these waters is fairly low. The tables indicate no use of LORAN except off Cape Hatteras. The four geographic areas described above require different types of navigation. For example, off Cape Hatteras use of beam fixing is highest, but is lowest from Buzzards Bay to Montauk. On the other hand, use of lookouts with binoculars is just the opposite. Obviously, requirements and information supplied must specifically suit each scenario or geographic area as well as consider the user's background and his equipment.

General data are available from comparing and contrasting major area differences. FIGURE B-4 breaks down the navigation workload and compares the duration and frequency of navigation related tasks on four major areas. The data in this illustration point to an increased workload during reduced visibility. As shown in FIGURE B-4 in the open sea, the mate spent 3.2 percent of his time in the chart room (calculating DR, reviewing charts, publications, etc), 3 percent of his time plotting fix data, 0.5 percent of his time taking radar fixes (to sea buoys, oil rigs, etc), and 3.4 percent of his time obtaining LORAN fix data. LORAN-A data were obtained and plotted about once an hour (0.8 and 1.1, respectively); OMEGA or satellite systems would probably be used equally in these situations.

Looking at the mate's workload in U. S. coastwise areas, where the navigation tasks require nearly 13 percent of his time, it may be seen in FIGURE B-4 that the mate stopped using LORAN (down to 0.5 percent) and switched to visual bearings (2.3 percent) or radar bearings (1.4 percent). FIGURE B-4 indicates that fixes were plotted at an average of 1.3 times an hour (once every 45 minutes). Visual fixes and radar fixes were taken of navigation aids as they became available. Note that 4.8 percent of the mate's time was then spent in the chart room performing general navigation tasks. These tasks, performed an average of 2.4 times each hour, include DR calculations and reviewing positions of navigation aids on the charts.

The higher average navigational workloads in the English Channel suggest a departure from the previous conclusions. The large difference between the two English

~~36,438,1607, 15,1,14, RADAR 1 RANGE~~  
~~36,438,1608,120,1,15, PLOT BR/R FIX, SETTING LEFT~~  
~~36,438,1611, 25,1, 4, BINOCULAR TO PINE SHOAL~~  
~~36,438,1612, 5,1,16, RADAR NO 1~~  
~~36,438,1612, 60,4, 2, STEER 254 DEG~~  
~~36,438,1619, 75,1,45, PELOROUS BR/BR~~  
~~36,438,1620, 75,1,15, PLOT BR/BR FIX~~  
~~36,438,1622, 60,1,45, PELOROUS BR/BR~~  
~~36,438,1623, 60,1,15, PLOT BR/BR IN CHART ROOM~~  
~~36,438,1624, 15,1, 8, LOG~~  
~~36,438,1625, 22,1,16, RADAR NO 1~~  
~~36,438,1625, 5,1, 8, LOG~~  
~~36,438,1626, 60,4, 2, STEER 262 DEG~~  
~~36,438,1630, 30,1,12, CHART ROOM~~  
~~36,438,1633, 8,1,60, BUOY BR AND R FROM IOTRON~~  
~~36,438,1633, 5,1,43, BUOY BR AND R RADAR NO 1~~  
~~36,438,1633, 85,1,15, PLOT BR/R TO NAV TOWER AT 030~~  
~~36,438,1634, 5,1,16, CHECK RADAR NO 1~~  
~~36,438,1635, 17,1,16, CHECK RADAR NO 1~~  
~~36,438,1636, 5,1,60, NAV MARK BR/R FROM IOTRON~~  
~~36,438,1637, 12,1,43, BR/R NAV AID RADAR NO 1~~  
~~36,438,1638, 0,1, 0, AMER. SHOAL 5.4 /282 DEG~~  
~~36,438,1640, 40,1, 7, BRIDGE WING, BINOCULAR NAV AID~~  
~~36,438,1643, 40,1,60, ACQUIRE BR/R NAV AID IOTRON~~  
~~36,438,1643, 5,1,43, CHECK IOTRON NAV AID~~  
~~36,438,1644, 90,1,15, PLOT BR/R NAV AID~~  
~~36,438,1646, 20,1,45, PELOROUS BR~~  
~~36,438,1646, 6,1,16, RADAR NO 1 AMER. SHOAL~~  
~~36,438,1646, 7,1,60, ACQUIRE BR/R IOTRON AMER. SHOAL~~  
~~36,438,1647, 65,1,15, PLOT BR/R AMER. SHOAL~~  
~~36,438,1648, 25,1,12, CHECK CHARTS ROOM~~  
~~36,438,1649, 60,1, 4, BINOCULARS NAV AID~~  
~~36,438,1650, 5,1,12, CHECK CHARTS~~  
~~36,438,1650, 39,1, 4, BINOCULARS NAV AID~~  
~~36,438,1651, 10,1, 4, BINOCULARS FOR MARYLAND~~  
~~36,438,1652, 19,1, 4, BINOCULARS FOR MARYLAND~~  
~~36,438,1652, 8,1, 4, BINOCULARS FOR MARYLAND~~  
~~36,438,1653, 60,3,24, CHANGE MATES~~  
~~36,438,1653, 10,3,43, AMER. SHOAL ON IOTRON~~  
~~36,438,1654, 20,3, 4, BINOCULARS FOR MARYLAND~~  
~~36,438,1654, 30,3,12, CHART ROOM~~  
~~36,438,1654, 45,3,45, PELOROUS BR/BR~~

Best Available Copy

FIGURE B-2. TYPICAL DATA BASE

	TASKS/HR
CHART ROOM TASKS	2.8
PLOTTING FIX DATA	0.5
RADAR RANGE AND BEARING	0.0
RADAR RANGE	0.5
LORAN-A	0.0
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	0.9
MONITOR RADAR	5.2
LOOKOUT W/BINOCULARS	2.8

BOSTON TO CAPE COD CANAL - 128 MIN.

	TASKS/HR
CHART ROOM TASKS	0.6
PLOTTING FIX DATA	0.6
RADAR RANGE AND BEARING	0.0
RADAR RANGE	0.9
LORAN-A	0.0
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	0.3
MONITOR RADAR	1.5
LOOKOUT W/BINOCULARS	2.9

BUZZARDS BAY TO MONTAUK POINT - 204 MIN.

	TASKS/HR
CHART ROOM TASKS	2.0
PLOTTING FIX DATA	1.3
RADAR RANGE AND BEARING	0.6
RADAR RANGE	0.7
LORAN-A	0.0
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	1.0
MONITOR RADAR	4.0
LOOKOUT W/BINOCULARS	2.7

FLORIDA KEYS AND COAST - 1335 MIN.

	TASKS/HR
CHART ROOM TASKS	3.1
PLOTTING FIX DATA	1.7
RADAR RANGE AND BEARING	0.5
RADAR RANGE	0.9
LORAN-A	0.3
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	1.9
MONITOR RADAR	3.5
LOOKOUT W/BINOCULARS	0.7

PAST CAPE HATTERAS - 640 MIN.

FIGURE B-3. EXAMPLE OF CONDENSED ANALYSIS OF A SPECIFIC NAVIGATION TASK ANALYSIS

	OPEN SEA	U. S. COASTWISE	ENGLISH CHANNEL	ENG. CHNL. LMTD. VIS.
GENERAL NAVIGATION TASKS	3.2%	4.8%	8.0%	22.2%
PLOT ALL FIX DATA	3.0%	3.8%	5.4%	9.4%
OBTAIN RADAR BR & R	.5%	1.4%	.9%	1.5%
OBTAIN LORAN-A DATA	3.4%	.5%	-	-
OBTAIN DECCA DATA	-	-	1.1%	.8%
OBTAIN RDF DATA	-	-	-	-
OBTAIN FATHOMETER DATA	-	.1%	-	-
OBTAIN VISUAL BEARINGS DATA	.1%	2.3%	.4%	.7%
OBTAIN SUN & STAR FIX DATA	-	-	.1%	-
TOTAL	10.2%	12.9%	15.9%	34.6%

Percent of Mates' Time

	OPEN SEA	U. S. COASTWISE	ENGLISH CHANNEL	ENG. CHNL. LMTD. VIS.
GENERAL NAVIGATION TASKS	.7	2.4	2.8	8.7
PLOT ALL FIX DATA	1.1	1.3	2.6	2.5
OBTAIN RADAR BR & R	.4	1.7	1.8	1.7
OBTAIN LORAN-A DATA	.8	.2	-	-
OBTAIN DECCA DATA	-	-	3.1	1.9
OBTAIN RDF DATA	-	-	-	-
OBTAIN FATHOMETER DATA	-	.1	-	-
OBTAIN VISUAL BEARINGS DATA	.1	1.2	.8	.5
OBTAIN SUN & STAR FIX DATA	-	-	.1	-
TOTAL	3.1	6.9	11.2	15.3

Number of Tasks Per Hour

FIGURE B-4. DURATION AND FREQUENCY OF NAVIGATION RELATED TASKS

Channel workloads is caused by different visibility conditions. Although an average of 2.5 fixes were plotted each hour under both visibility conditions (approximately one fix every 20 minutes), more time was spent to plot fixes (9.4 percent versus 5.4 percent) under conditions of limited visibility. This increase does not indicate that plotting the fix takes longer; however, the mates may have been working more cautiously in their analysis of the resultant fix and its relation to upcoming navigation aids.

This increased task behavior also appeared in the general navigation tasks (DR calculations, study charts, etc). Although the mates' time for these tasks under limited visibility nearly tripled those of unlimited visibility (22 percent versus 8 percent), the reader may note that the number of times per hour these tasks were performed also tripled (8.7 versus 2.8); therefore, the average task duration remained the same. The mate apparently checked DR and charts more often in limited visibility.

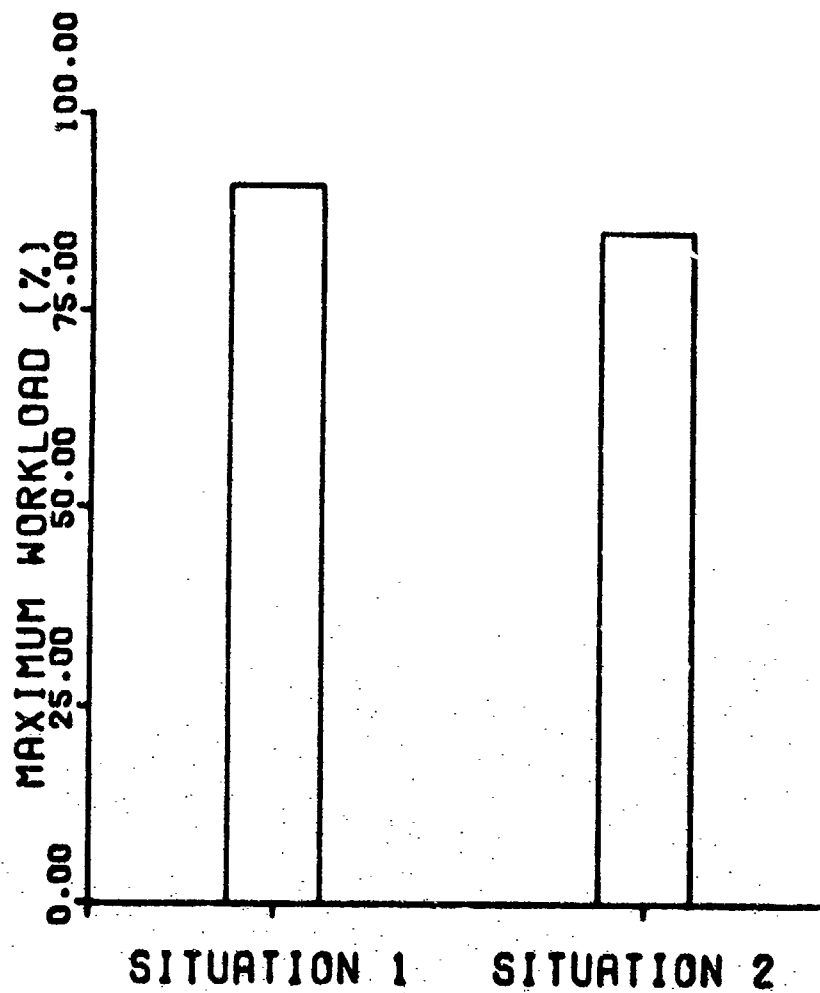
The highest navigation loads recorded often occur when own ship enters or crosses navigation lanes in the English Channel. Often, these situations required evasive maneuvering concurrent with navigation tasks and presented the mates with both peak contact assessment and navigational loads. FIGURE B-5 indicates the navigational loads exhibited by mates during two evasive maneuvering situations recorded in the English Channel under limited visibility. In these two situations, the mate on watch spent between 85 and 90 percent of his time navigating while the contact assessment function and evasive maneuvering were performed by a North Sea Pilot.

Here, for the first time, portions of the navigation function may be considered lacking. In short, the mate was not provided with accurate timely AN information under these specific conditions, and he obviously has the requirement.

a. Analysis of Visual Fixing Navigation Tasks and Equipments. The at-sea data base indicates that visual fixes are used to the greatest extent in U. S. coastal waters. FIGURE B-6 illustrates this fact by plotting the mates' workloads for obtaining visual fixes across all the navigational divisions of the data base. Two types of visual fixes are indicated in these data: (1) a bearing fix obtained by sighting a navigation aid with a pelorus ring mounted on the ship's gyro compass; and (2) a beam fix, which involves sighting a navigation aid directly abeam without the pelorus. Pelorus bearing fixes were generally used when ownship was several miles from a navigation aid; navigation aids within a 2 to 4 nautical mile range were regularly sighted with beam fixes. Beam fixes were logged extensively when ownship was in channel, river, or pilot waters.

The data in FIGURE B-6 indicate the average task durations of pelorus sightings and visual beam fixes. The relatively long time taken by these tasks (53 to 88 seconds) indicates that the mates were waiting either for the proper alignment or for time to take the fix data. This is evident in the beam fix data; mates were observed to continuously watch an aid until it was directly abeam. Similarly, mates were often observed to delay taking a pelorus fix until a predetermined time was reached (e.g., the quarter hour, the half hour). Another factor contributing to lengthy visual fixes was the necessity to see the navigation aid and identify it properly. Marginal visibility often forced mates to use binoculars over the pelorus to locate an aid. Additionally, at night, mates were required to verify the proper light signal code to be certain of the identity of the aid. These night fixes, which were observed to take an additional 20 to 30 seconds, were recorded in the data base as part of the overall visual fix time.

b. Analysis of Electronic Fixing Tasks and Equipments. Data collection at sea was segmented so that it was possible to determine the mate's workload and frequency for obtaining most electronic fix data prior to plotting. The six navigation systems observed



**FIGURE B-5. PEAK NAVIGATIONAL WORKLOADS EXHIBITED IN THE  
ENGLISH CHANNEL, LIMITED VISIBILITY  
(SITUATION 1, CROSSING; SITUATION 2, MANEUVERING)**

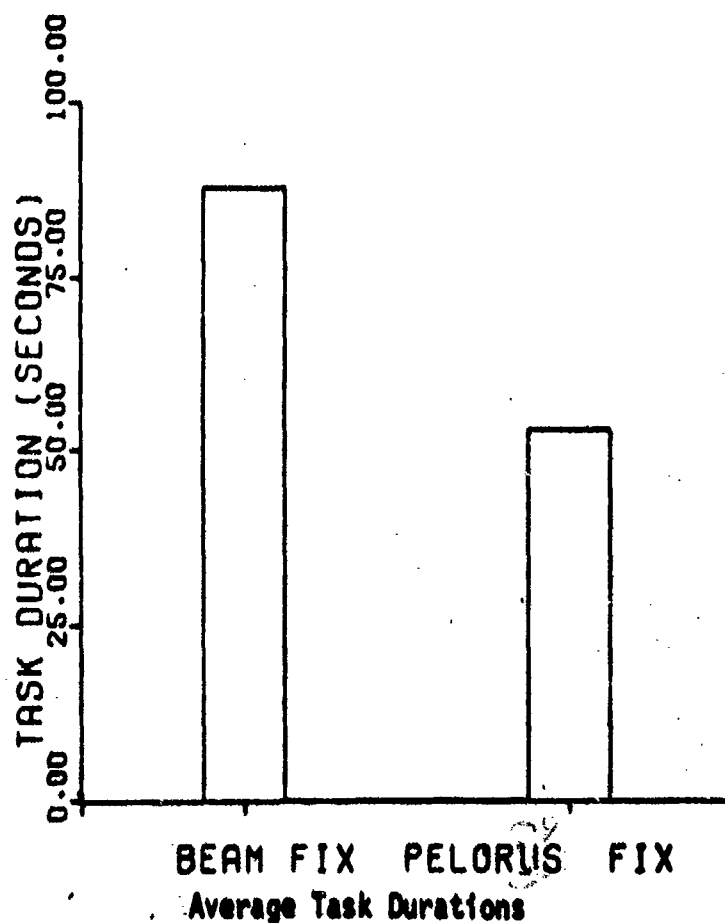
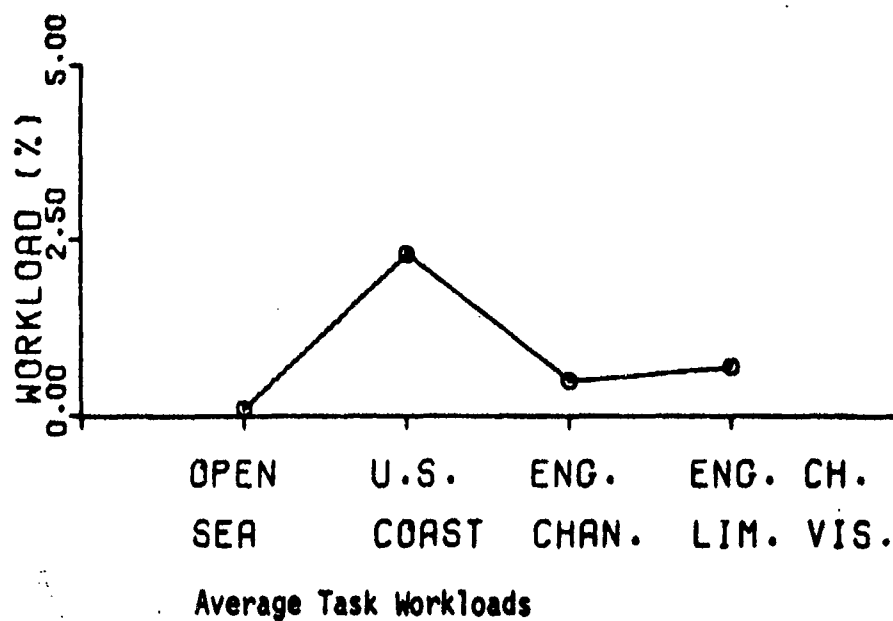


FIGURE B-6. AVERAGE WORKLOADS AND TASK DURATIONS FOR PELORUS SIGHTINGS AND VISUAL BEAM FIXES

at-sea were: radar, LORAN-A, satellite, Decca, fathometer, and radio direction finder (RDF).

FIGURE B-7 shows the mate's average workloads for obtaining radar fix data; the lower half of FIGURE B-7 shows the frequency of fixes. These data indicate that the mate required less than 2 percent of his time to obtain approximately two fixes per hour. As would be expected, radar appears to be used primarily in the U. S. coastwise area and in the English Channel. The mean time durations required to obtain radar fixes are indicated in FIGURE B-8. The first bar indicates the mean time required to obtain a bearing or range on a standard radar PPI; the second bar indicates the mean time required to obtain bearings or range information on a collision avoidance display.

Three alternate LORAN systems, two Decca systems, and two satellite receivers were examined. The data in FIGURE B-9 indicate the average workloads for mates to obtain LORAN-A or Decca fix data. The frequencies of taking data are indicated in the lower half of FIGURE B-9. These data indicate exclusive reliance on LORAN (OMEGA, satellite, etc) in the open sea. Fixes were taken about once an hour in these waters. Reliance on the Decca system was seen in the English Channel: fix frequency in these waters is up to 3 per hour.

The data in FIGURE B-10 indicate the average fix acquisition times for the first two LORAN sets and the two Decca sets. The data for the first LORAN set (manually operated) indicate that fixes for two or three LORAN-A stations were obtained in about 142 seconds. Automatic tracking of one station reduced the performance time to only 102 seconds. The small reduction in task duration is because a LORAN fix requires a minimum of two points (typically, three points), and to obtain a second point, the receiver must be manually retuned to another station, thus negating the work reduction realized by automatic tracking.

Performance time with the LORAN-C set could be expected to be similar to that indicated for the Decca receivers because fixes for the two stations were available continuously. Fix data were available in digital form; the mate needed only to write the numbers on a sheet of paper for plotting. Estimations based on Decca observation imply that this task would take less than 15 seconds. However, a problem exists for this system. Users complain that a three-station fix is often desired, forcing manual retuning of the receiver. This additional task would increase fix-acquisition time to a point comparable with the two LORAN-A receivers (100 to 140 seconds).

Fix-acquisition time shown in FIGURE B-10 for the Decca sets was approximately 15 seconds. This time reflects the tasks of waiting for a good set of values, viewing the output display, and sequentially writing down the time delays for three Decca stations. Manual tuning of the set is required only at the beginning of a voyage, when changing from one chain to another, and perhaps once or twice during port-to-port passages in the English Channel. A task duration of 1 minute and 20 seconds was recorded for the task of retuning the Decca receiver to a new chain of stations. This task time was not added to the task data in FIGURE B-10.

An interesting use of Decca receivers was reported by mates on one of the ships observed. They felt that the digital display of Decca station time delays was useful in itself for keeping continuous mental track of ownship position. It was reported that such a familiarity with the Decca numbers had been developed over several years and that ownship's position could be determined without plotting the data.

c. Analysis of General Navigational Tasks. It was observed that mates at sea regularly returned to the chart room to review charts and publications. Much of this



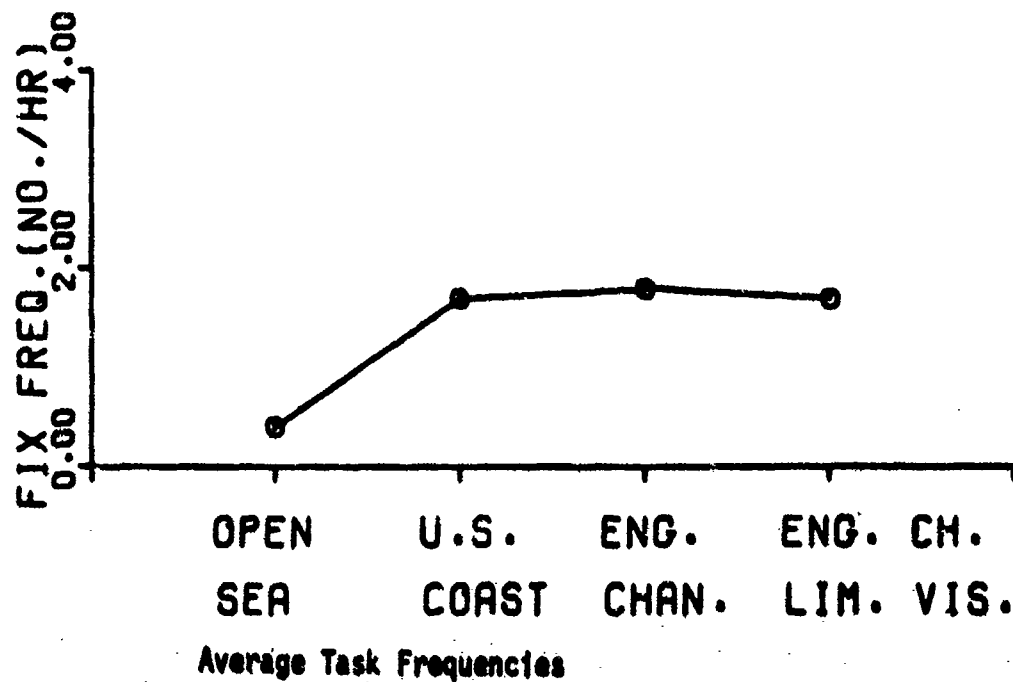
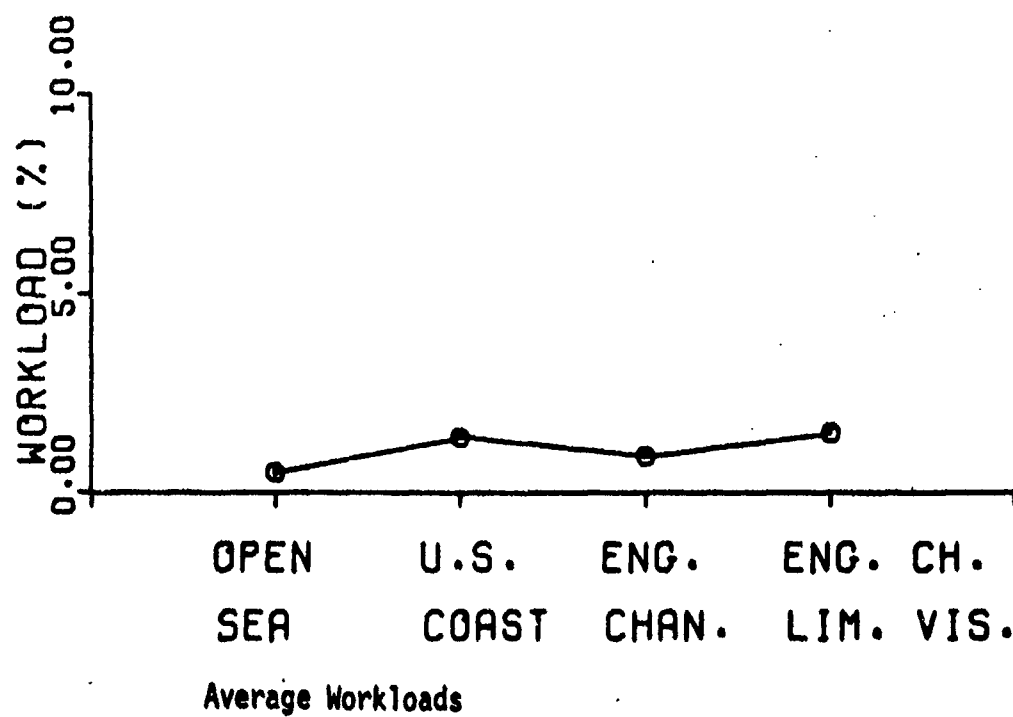
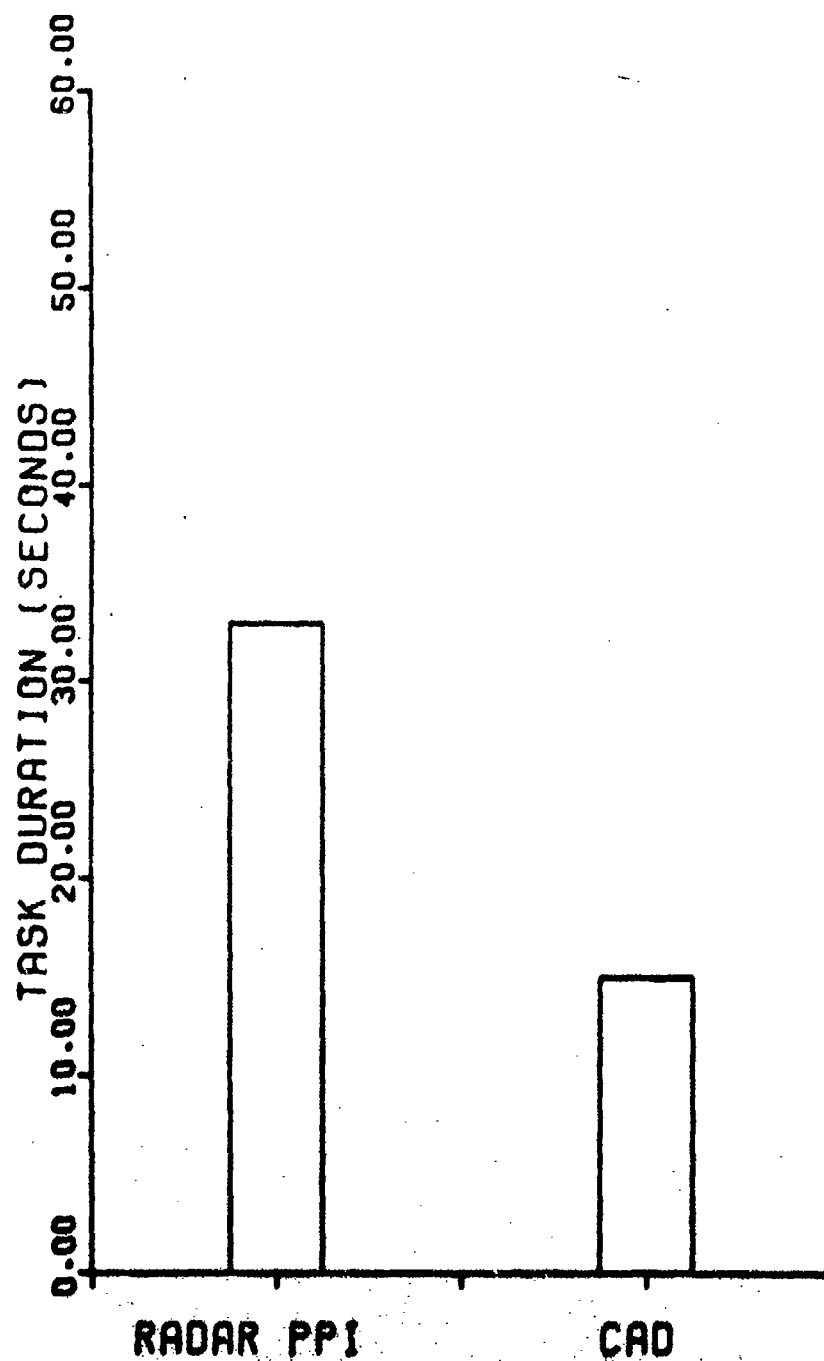
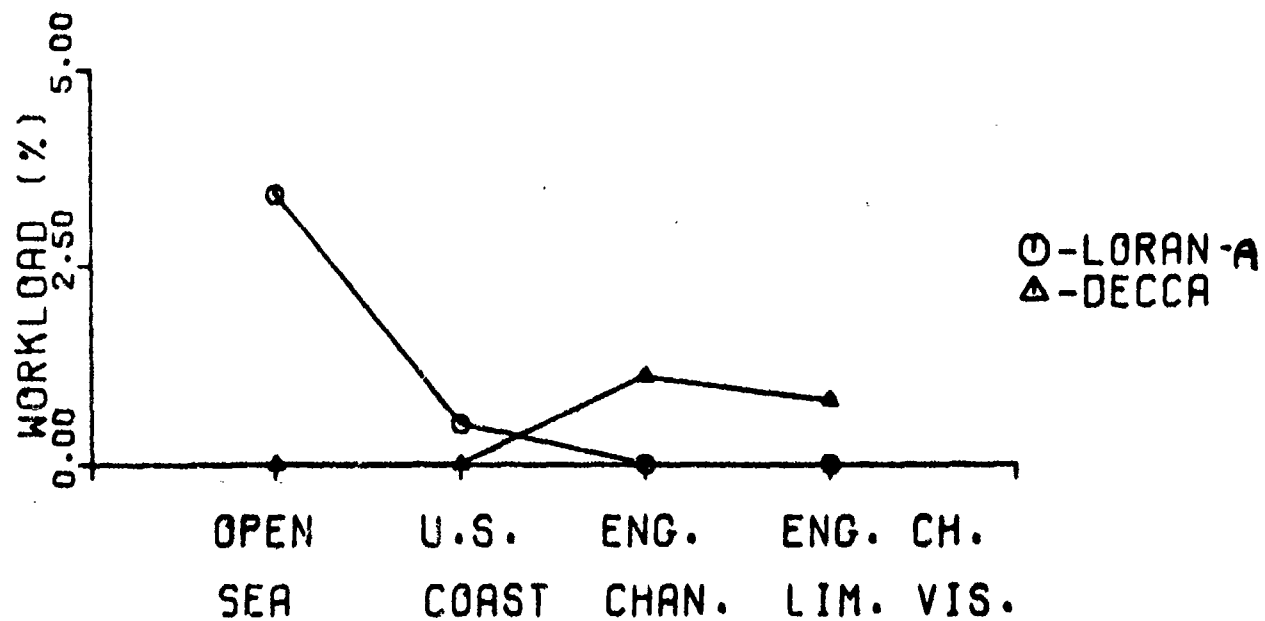


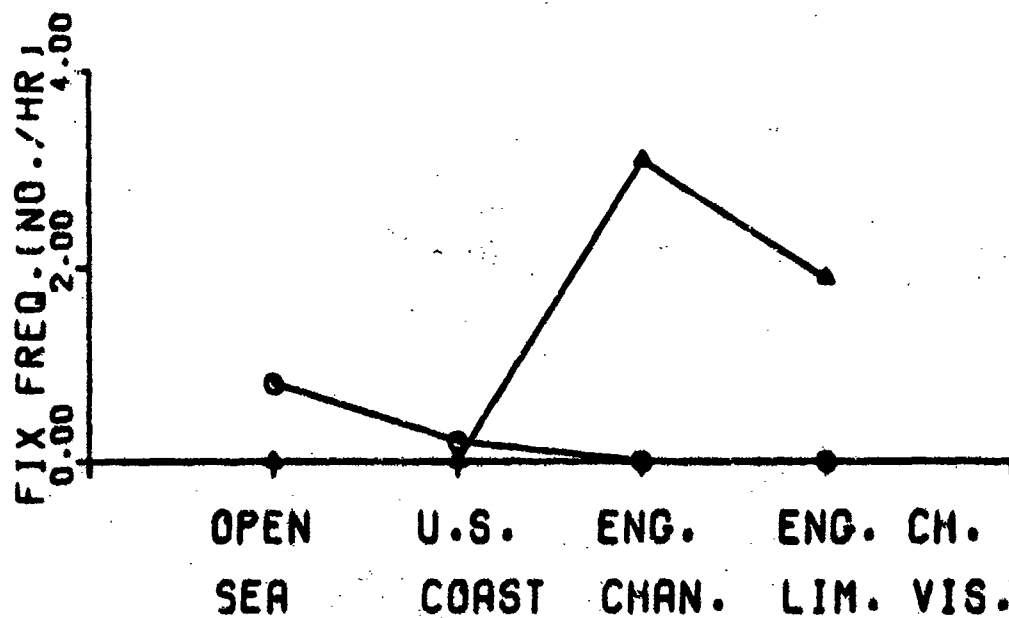
FIGURE B-7. AVERAGE WORKLOADS AND TASK FREQUENCIES TO OBTAIN RADAR FIX DATA



**FIGURE B-3. AVERAGE TASK DURATION TO OBTAIN RADAR RANGE AND BEARING FIX DATA ON RADAR PPI (PLAN POSITION INDICATOR) AND CAD (COLLISION AVOIDANCE DISPLAY).**



2.8.1. Average Workloads



2.8.2. Average Task Frequencies

FIGURE B-9. AVERAGE WORKLOADS AND TASK FREQUENCIES TO OBTAIN LORAN-A AND DECCA FIX DATA

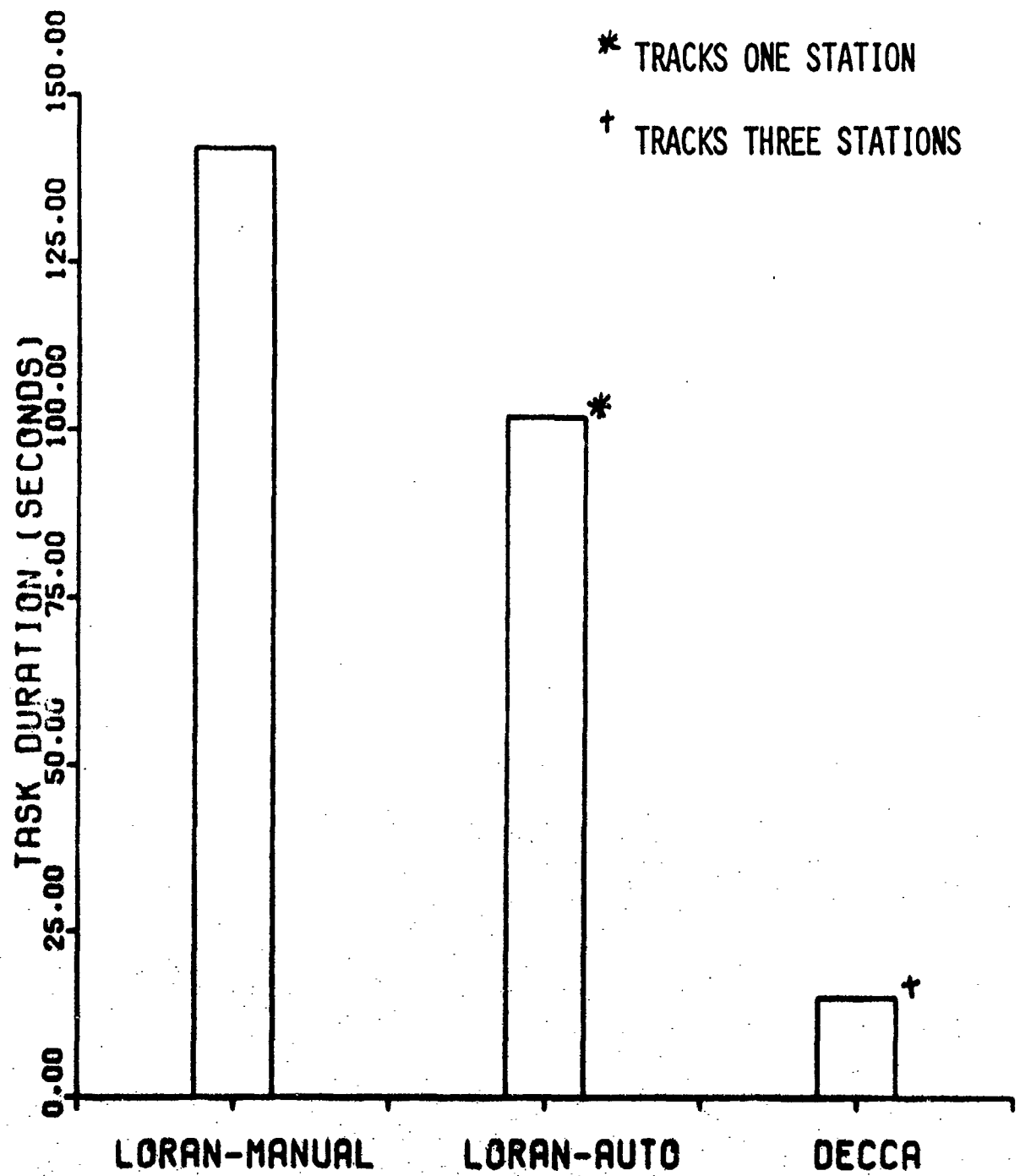


FIGURE B-10. AVERAGE TASK DURATIONS TO OBTAIN LORAN-A AND DECCA FIX DATA

behavior can be attributed to the desire to double check position fixes and to correlate observed information with that found on charts. This section briefly reviews the behavior exhibited by the mates during these tasks. The mates' workloads in performing general navigational tasks and task frequencies are indicated in the graphs in FIGURE B-11. Both workload and frequency increased as navigational hazards increased and visibility became limited. Since frequency increased with the total workload increase, it can be expected that the mean task duration remained somewhat constant. This is verified in FIGURE B-12, where the mean general navigation task duration is plotted across the navigation areas. These data indicate that the average time spent in the chart room was between 1-1/2 and 2 minutes. However, these values are misleading as can be seen in the graph in FIGURE B-13, which indicates that the duration of general navigation tasks was evenly distributed between 10 seconds and 4 minutes. This distribution, recorded in the English Channel under limited visibility, is typical of that found in all navigational areas. The short duration tasks of 5 to 25 seconds typify "detection" behavior (e.g., checking charts, determining navigation aids and identity). The longer tasks of 25 to 240 seconds typify "analytical" behavior (e.g., performing DR calculation, correlating navigation aid positions against those on radar, checking publications). If many of the analytical tasks could be removed from the mate's workload, the mate's overall navigational workload might be reduced. In conclusion, a high-quality navigation system should provide a continuous plot of ownship position. This is the ultimate requirement of ships' officers.

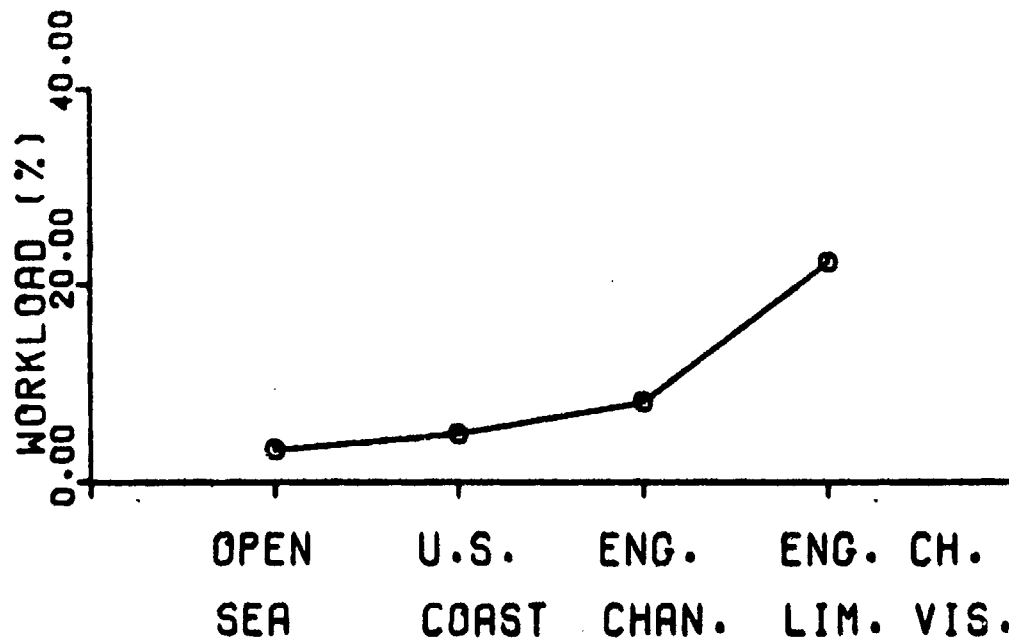
#### B.1.2 Scenario Two - Harbor Approach

Scenario Two concerns harbor approach zones where vessels arrive from the open sea. FIGURE B-14 shows a typical harbor approach, New York Harbor. Aids to navigation available here include buoys, beacons, lighthouses, directional radio beacons, RACON, OMEGA, LORAN, and satellite navigators. Transition from open sea navigation to piloting is crucial, especially during heavy weather which may make visual and electronic navigation difficult. The navigator must check the accuracy of his previous navigation (celestial, LORAN, OMEGA, or NAVSAT); if in error, this could lead to an inaccurate landfall. This check involves soundings (2 to 100 nautical miles), visual detection of a major light or lightship (10 to 25 nautical miles), appearance and identification of land or ANs on the radar (10 to 50 nautical miles), and in some cases an RDF fix (20 to 200 nautical miles). At-sea data indicate the transition to piloting: hourly LORAN fixes switching to every 15 minutes with a confirming RDF fix; then radar and pelorus fixes at 15-minute intervals when land is in range, eliminating reliance on LORAN (reference 27). Ship control is through course orders to the helmsman.

Scenario Two also includes the outer harbor approach where the ship must locate the pilot station or where the navigator (if the master has pilotage for the port) must locate and proceed to the sea buoy. The prime navigational methods are visual and radar piloting. Depending on AN locations, radar fixes are ranges abeam, bearing, and range or standoff range from the cursor. Use of radar depends on visibility, time of day, and traffic density although other considerations can be important: these are resolution of the radar, skill of the operator, topography of the port, and number of radar reflective navigational aids.

FIGURE B-15 is a computer analysis of selected segments of the at-sea data base of reference 26. These data again indicate the geographically specific nature of the ship's officer navigation task and its requirements. The reader will observe an increased use of LORAN over the conditions of Scenario One.

The use of radar included ranges only, ranges and bearings, and monitoring, without plotting. The radar range and bearing fixes were few since this method is the least



2.16.1. Average Workloads

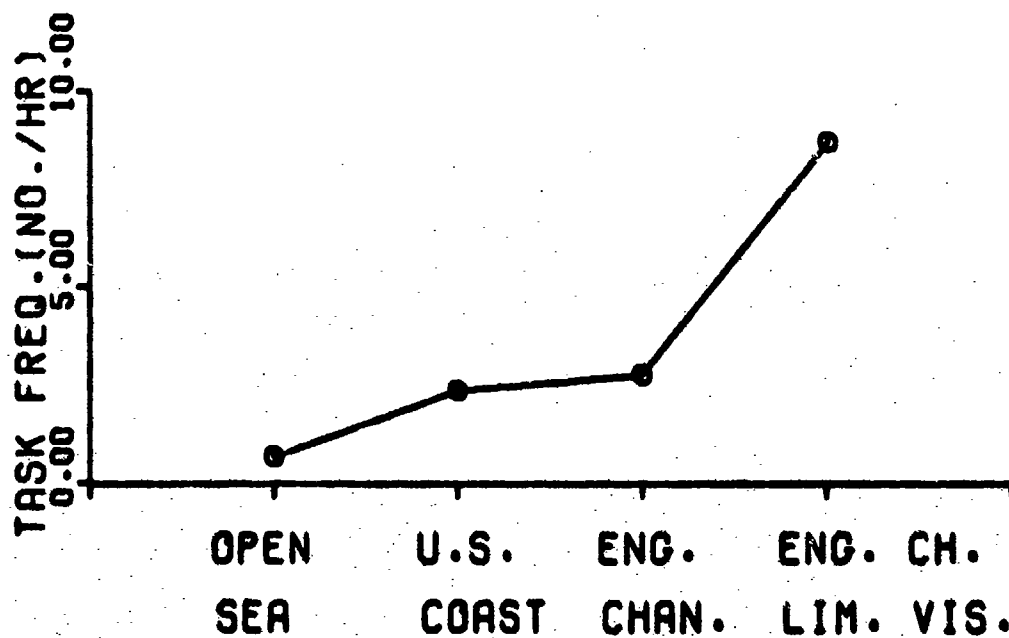


FIGURE B-11. AVERAGE WORKLOADS AND TASK FREQUENCIES OF GENERAL NAVIGATION TASKS PER NAVIGATION AREA, ALL CONTACT DATA

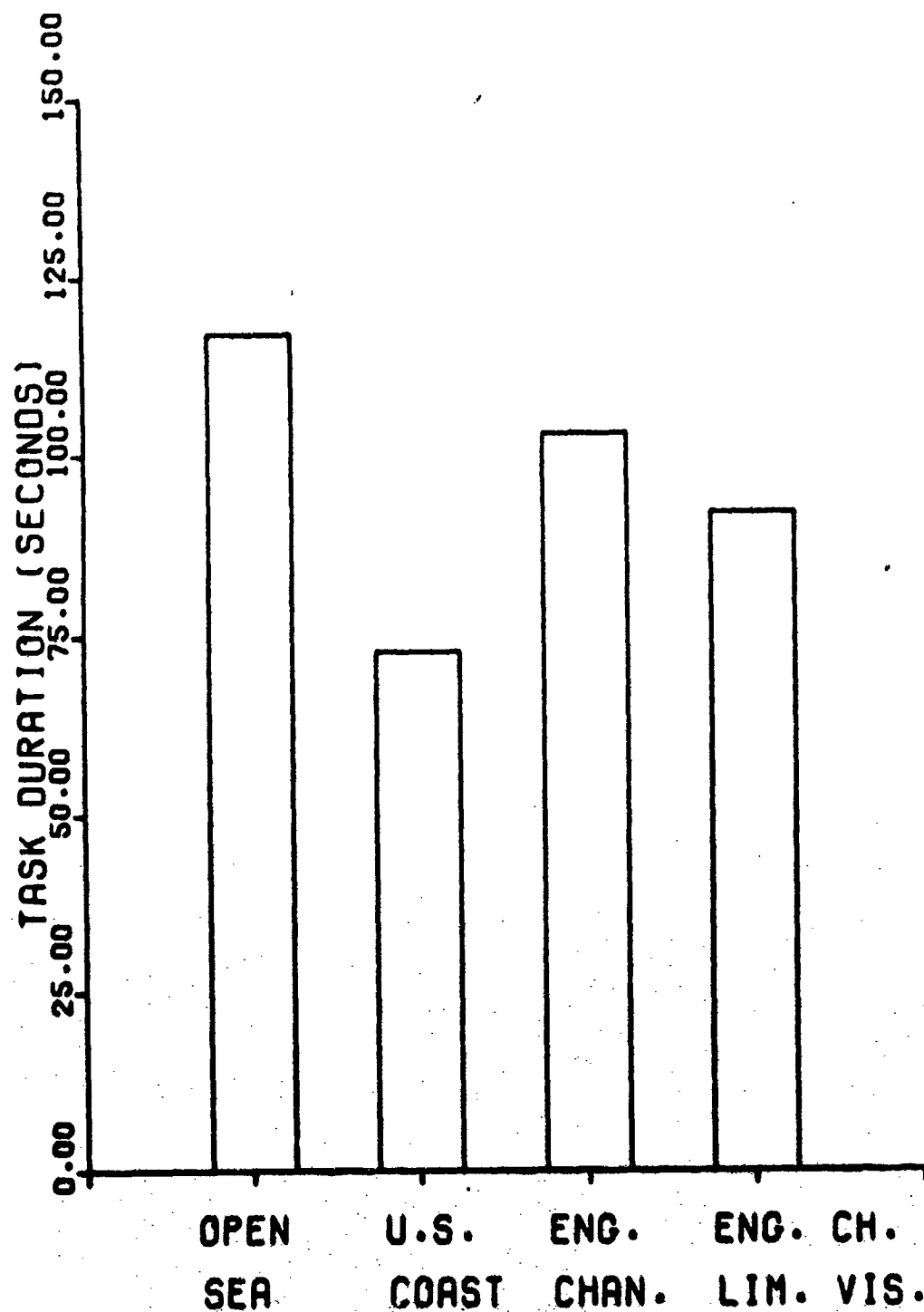
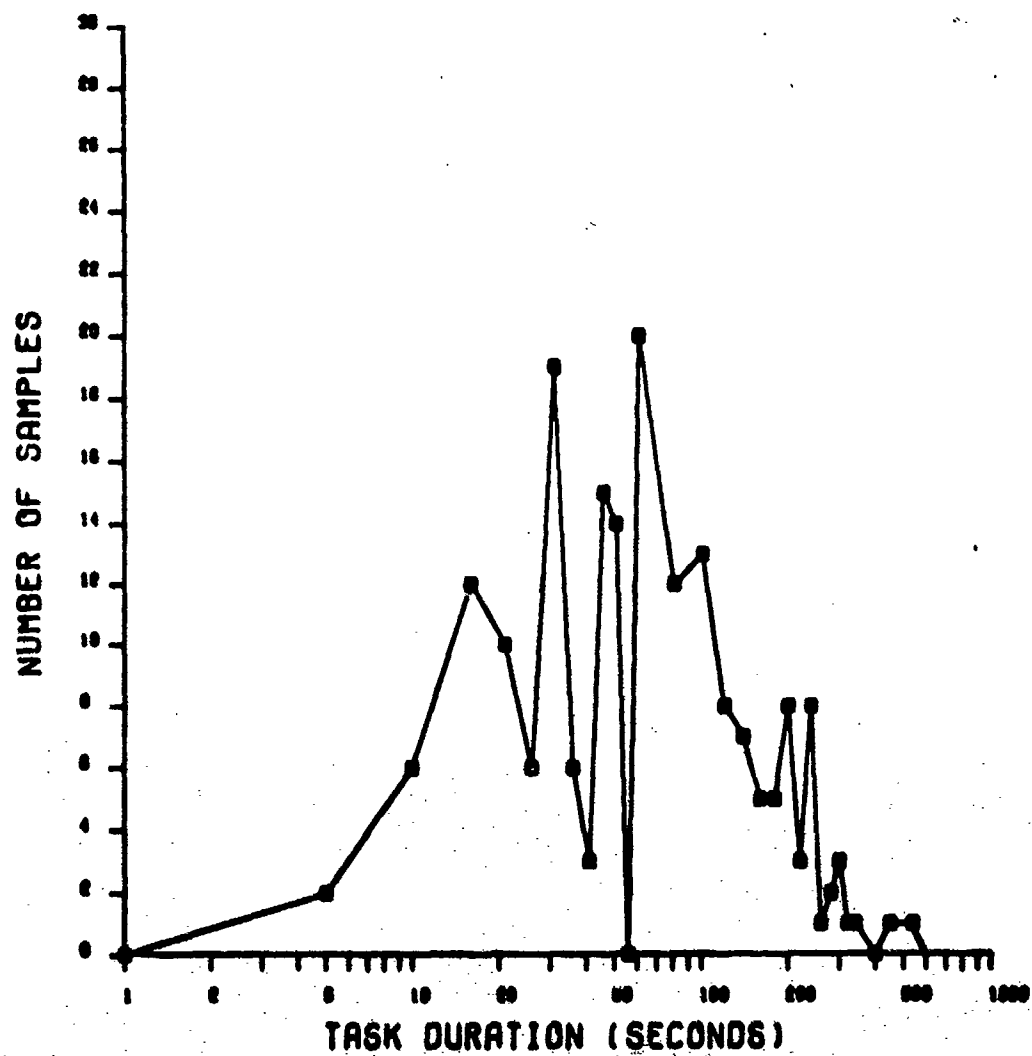


FIGURE B-12. AVERAGE TASK DURATIONS FOR GENERAL NAVIGATION TASKS PER NAVIGATION AREA, ALL CONTACT LOAD DATA



**FIGURE B-13. FREQUENCY DISTRIBUTION OF THE DURATION OF GENERAL NAVIGATION TASKS, RESTRICTED WATERS/LIMITED VISIBILITY**



BUOYS  
 BEACONS  
 RACON  
 LIGHTHOUSES  
 RDF  
 LORAN

MASTERS & MATES FIX METHODS	
LORAN	1 HR
RDF	ONCE
RADAR	15 MIN
PELORUS	15 MIN

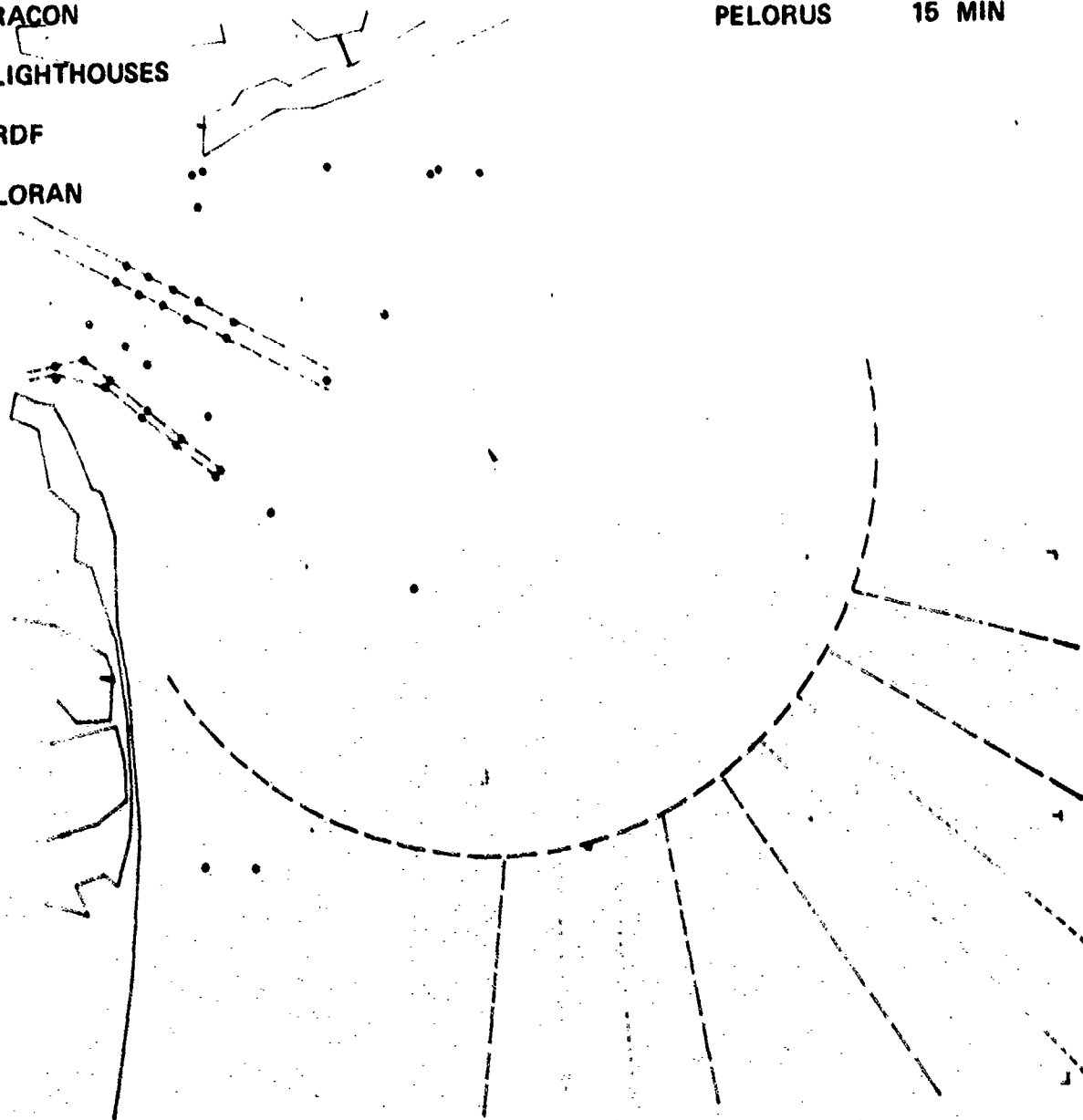


FIGURE B-14. SCENARIO TWO, HARBOR APPROACH

	TASKS/HR
CHART ROOM TASKS	2.7
PLOTTING FIX DATA	1.9
RADAR RANGE AND BEARING	0.6
RADAR RANGE	0.6
LORAN-A	0.8
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.4
VISUAL BEAM FIX 7 PELORUS	1.1
MONITOR RADAR	1.9
LOOKOUT W/BINOCULARS	1.5

PORT APPROACH NEW ORLEANS - 284 MIN.

	TASKS/HR
CHART ROOM TASKS	0.6
PLOTTING FIX DATA	1.4
RADAR RANGE AND BEARING	0.0
RADAR RANGE	0.8
LORAN-A	1.1
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	0.0
MONITOR RADAR	1.4
LOOKOUT W/BINOCULARS	1.1

APPROACH TO CAPE MAY - 214 MIN.

	TASKS/HR
CHART ROOM TASKS	1.5
PLOTTING FIX DATA	0.7
RADAR RANGE AND BEARING	0.0
RADAR RANGE	1.6
LORAN-A	0.4
DECCA	0.0
RADIO DIRECTION FINDER	0.1
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	0.8
MONITOR RADAR	1.7
LOOKOUT W/BINOCULARS	1.2

APPROACH TO JUPITER POINT - 569 MIN.

	TASKS/HR
CHART ROOM TASKS	4.2
PLOTTING FIX DATA	0.9
RADAR RANGE AND BEARING	0.0
RADAR RANGE	1.4
LORAN-A	0.9
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	0.0
MONITOR RADAR	6.1
LOOKOUT W/BINOCULARS	3.7

APPROACH TO WILMINGTON N C - 128 MIN.

	TASKS/HR
CHART ROOM TASKS	1.7
PLOTTING FIX DATA	0.0
RADAR RANGE AND BEARING	0.0
RADAR RANGE	0.8
LORAN-A	0.0
DECCA	0.0
RADIO DIRECTION FINDER	0.0
FATHOMETER	0.0
VISUAL BEAM FIX 7 PELORUS	0.0
MONITOR RADAR	5.4
LOOKOUT W/BINOCULARS	4.1

NIGHTTIME OUTER HARBOR - SABINE HARBOR - 145 MIN.

FIGURE B-15. COMPUTER ANALYSIS OF SELECTED SEGMENTS OF AT-SEA DATA BASE

accurate due to gyro and beamwidth-induced bearing errors. Much more dependence on range only solutions was noted from an analysis of the data. The monitoring of the radar was the most. This task includes detection of ships, their continued observation, detection of land, and the watch on the proximity of land. Visual lookout tasks were recorded almost as frequently as radar monitoring. These tasks were most frequent during the outer harbor transit where collision avoidance and navigation are equally critical problems. Some use of pelorus for visual bearings was observed during Scenario Two type conditions, however, it was not used during the outer harbor piloting (Scenario Three).

#### **B.1.3 Scenario Three, Four, Five - Outer Harbor Approach, Inner Harbor Channel, and River**

The third scenario, the outer harbor approach, is entered from the sea buoy. FIGURE B-16 shows a typical outer harbor channel system. The vessel must be piloted through the approach channels, usually wider than the inner harbor channels. Buoys, beacons, ranges, leading lights, daymarks, and minor lights give the pilot the information he needs to maintain his position within the channel. This piloting task is known as a continuous fix. Actual observations indicate two methods: visual observation every 10 to 30 seconds and radar every 3 to 6 minutes. Radar fixes are, primarily, range to AN abeam and standoff ranges. Bearings and ranges to known objects (local knowledge) are occasionally used. Ship control is maintained through course orders and rudder orders in turns.

Scenario Four is inner harbor channel piloting shown in FIGURE B-17. Here, the practice of navigation relies heavily on visual observation. A continuous fix process is used, but may consist of several piloting methods combined. Visual and radar buoys, ranges, daymarks, and lighthouses provide navigation information; the pilot's methods and frequencies are visual (every 10 to 30 seconds), radar (every 3 to 6 minutes), and VTS (every 5 to 10 minutes). Traffic avoidance is usually not complicated by severe currents except in selected areas of certain ports (for example, Hell Gate in the East River, New York). Traffic density in these channels may be greater in major ports as traffic patterns converge and cross. Ship control may rely exclusively on rudder commands by the pilot.

Scenario Five is river navigation where a pilot must maintain his channel position while avoiding bridges, traffic, and other hazards. FIGURE B-18 shows typical geography and ANs available. Except for certain aspects in ship handling, this scenario is similar to Scenario Four. Navigation on the river is further complicated by the current, snags, shifting shoals, narrow bridges, and traffic which is unable to maneuver effectively. Blind curves with tricky current effects can pose traffic avoidance and maneuverability problems. Course orders are usually issued in straight legs; rudder orders are given in turns.

FIGURES B-19 and 20 show a broad data compilation of pilot activity under this type of scenario condition as taken from reference 27. These figures offer supporting data on the continuous nature of the visual process, the majority of which is directed straight ahead. The reader should again note the geographically specific nature of many of these visual tasks.

These last scenarios underscore the point that the navigation process in the harbor area depends highly on visual means and that fix is in question much of the time requiring a continuous monitoring function. If the navigator has a need beyond the existing AN system, it is simply for a continuous accurate fix of his position that can best be provided electronically.

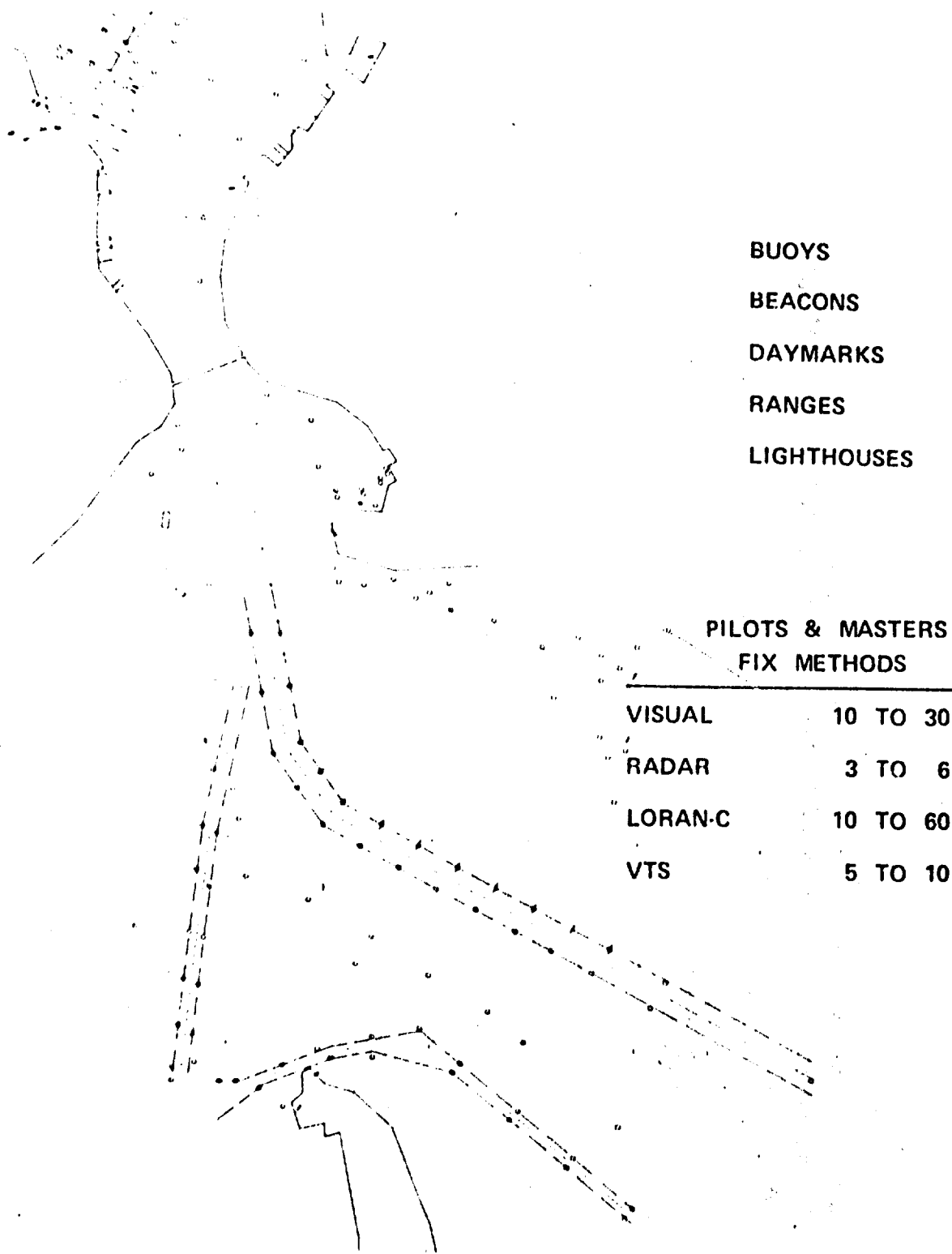


FIGURE B-16. SCENARIO THREE, OUTER HARBOR APPROACH

PILOTS & MASTERS  
FIX METHODS

VISUAL	10 TO 30 SEC
RADAR	3 TO 6 MIN
VTS	5 TO 10 MIN

BUOYS  
RANGES  
DAY MARKS  
LIGHTHOUSES

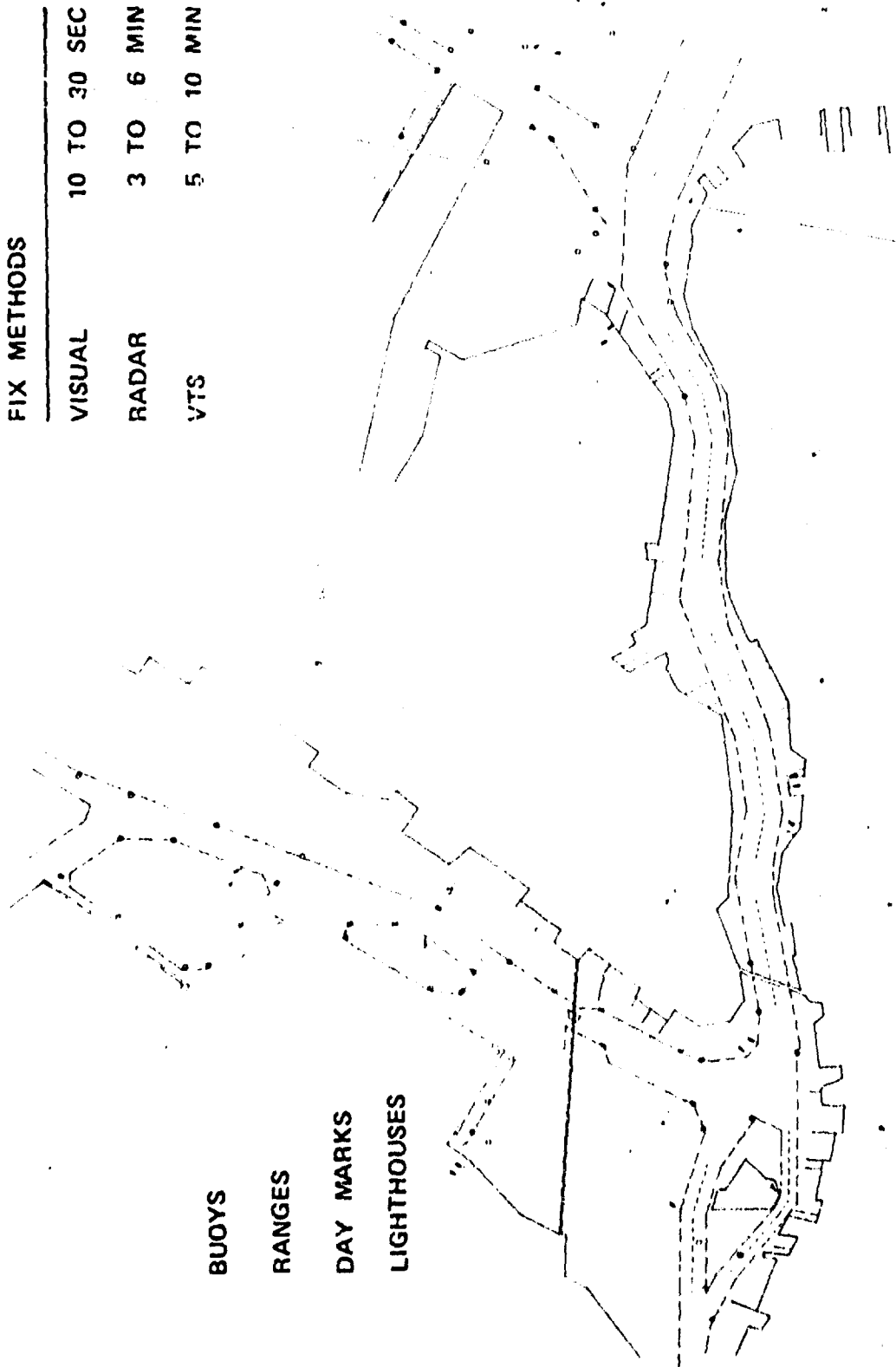


FIGURE B-17. INNER HARBOR CHANNELS

PILOTS & MASTERS  
FIX METHODS

VISUAL	10 TO 30 SEC
RADAR	3 TO 6 MIN
LORAN-C	10 TO 60 SEC
VTS	5 TO 10 MIN

BUOYS  
RANGES  
DAY MARKS  
LIGHTHOUSES

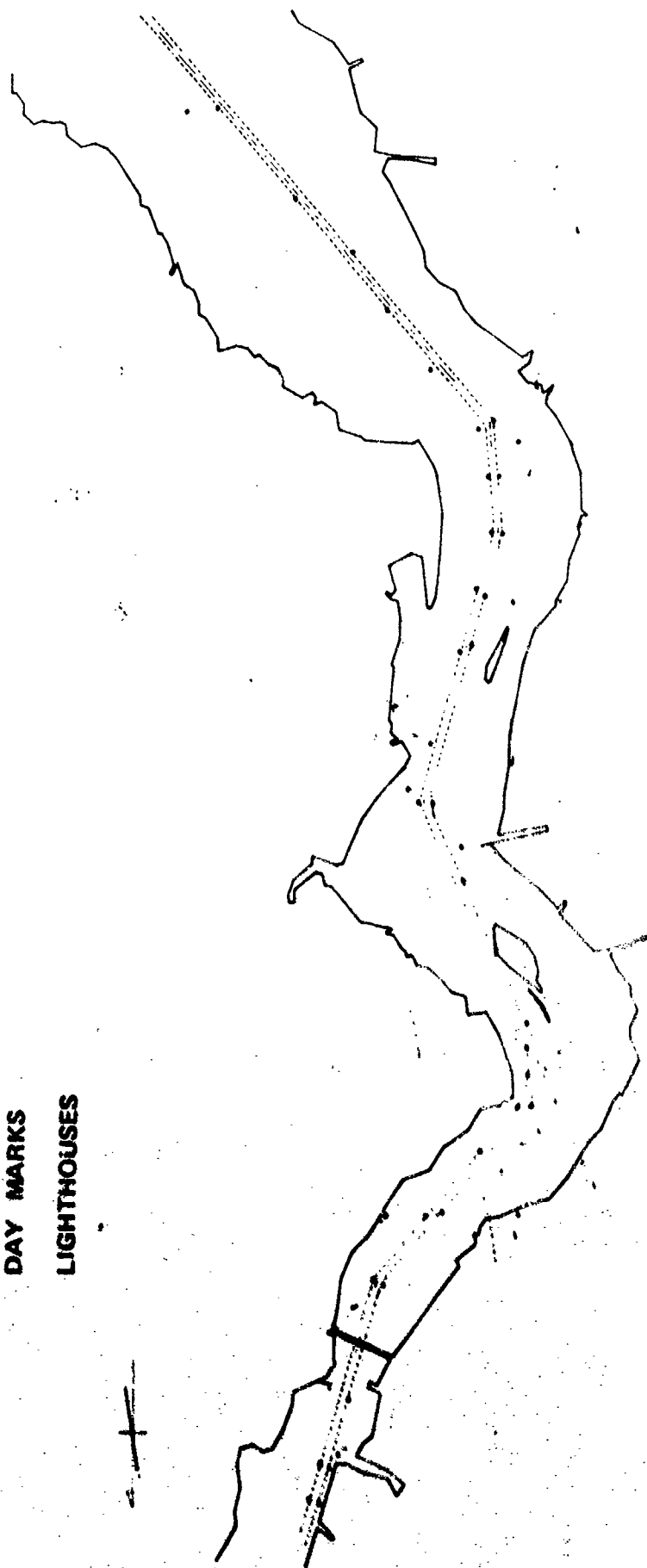


FIGURE B-18. SCENARIO FOUR, RIVER SYSTEMS

FIGURE B-19. DATA COMPILATION OF PILOT ACTIVITY (INSIDE VISUAL)

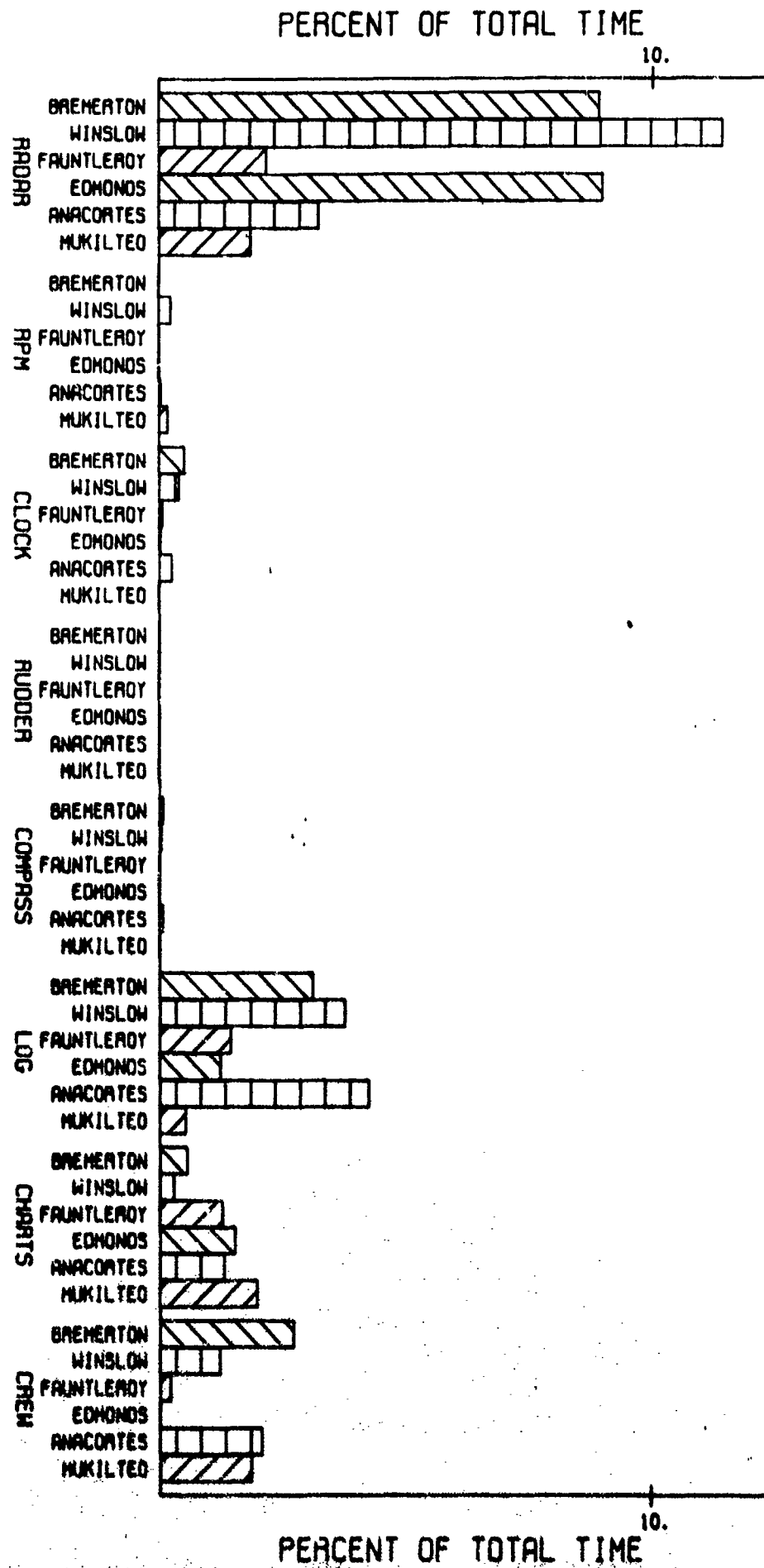
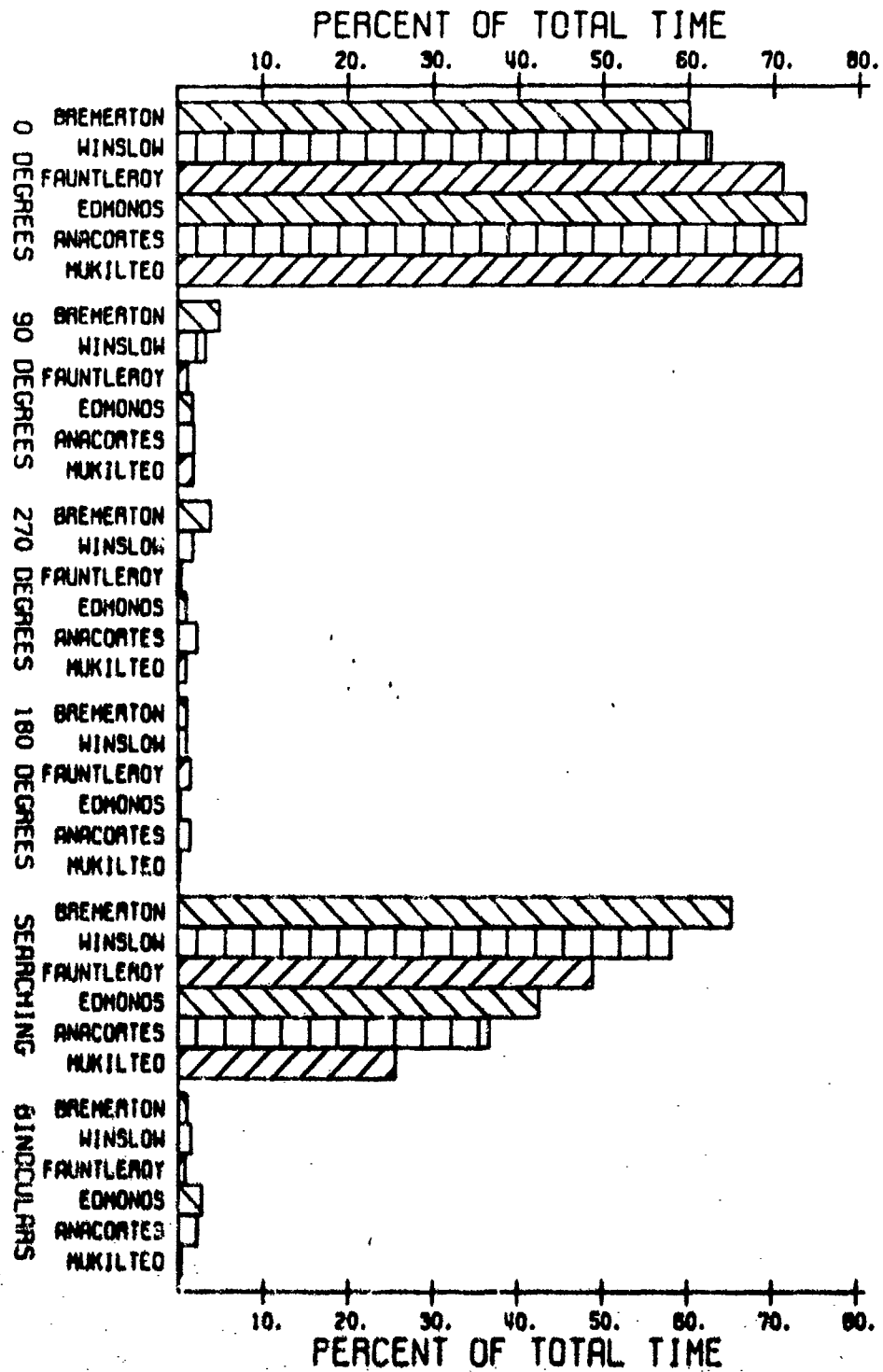


FIGURE B-20. DATA COMPILATION OF PILOT ACTIVITY (OUTSIDE ACTIVITY)





## B.2 AID TO NAVIGATION INFORMATION REQUIREMENTS

The process of navigation in all five scenarios discussed in Section B.1 require similar navigational tasks. The frequency of performance of these tasks, accuracy, and the need for the task at all depend on the scenario, weather conditions, and traffic. Tasks that are primary contributors to the process of navigation follow:

- Along track position estimate
- Cross track position estimate
- Course made good estimate
- Speed, along and cross track estimate
- Wind effects estimate
- Current effects estimate
- Bank and bottom effects estimate
- Ship response-to-helm orders estimate
- Responses to traffic problems
- Navigating the ship through decisions and actions.

These tasks are discussed below in light of their potential requirement for AN information in various scenario types.

### B.2.1 Along Track Position Estimate

The navigator must be able to determine vessel position along the intended track only at specific points. The along track position is important for indicating turn or course change positions and for predicting the time of landfall. While navigating in Scenario Three, Four, and Five waters, this position is determined by buoy identity and knowledge of the sequence of aids in the channel. The number, structure and light characteristics of buoys, beacons, or daymarks provide along track information as do prominent landmarks and topography ashore. Proper identification of ANs by the professional mariner is generally not a problem, but it is with recreational boaters and foreign crews.

Using a pelorus or radar, ranges and bearings to known ANs will indicate the along-track position for Scenarios One and Two. The methods used in the five scenarios include crossing the DR track with a line of position or obtaining a fix using two lines of position. Bearing of objects on the beam provide an accurate along-track position whether taken visually or by radar. This method is used in all scenarios.

In absence of the above methods, the navigator must rely on his DR position to estimate along track position and, in this case, should not attempt landfall course changes.

### B.2.2 Cross Track Position Estimate

The cross track position indicates the distance the ship has strayed from the track and, if known, indicates the distance from hazards to navigation. This position (Scenarios Three, Four, and Five) can be indicated by the range to buoys, which is most accurately estimated when abeam of the buoy. Relative bearings to ANs, and particularly the

establishment of a series of gated buoys as a pseudo range, provide important indication of cross track position. Fixed channel ranges, whether lighted or composed of natural features, provide an accurate cross track position indicator. Harbor and river pilots rely heavily on ranges. The range abeam to known landmarks or fixed ANs will determine the cross track position; however, only radar is normally of sufficient accuracy to determine whether the ship is in the channel (and this is questionable based on at-sea and simulator observations). Other piloting methods that can be used visually or with radar when only one object is available are bow and beam bearings and doubling the angle on the bow.

Other navigational methods indicating cross track position required plotting on a chart. Radar ranges and bearings, visual or radar bearings of two or more objects, LORAN fixes, and Decca (if available) are extensively used for Scenarios One and Two navigation. Radio direction finder fixes are used occasionally when there is reason to doubt the accuracy of other methods. Recreational boating safety depends heavily on this system because of the low cost of receiving equipment. Soundings can sometimes indicate position especially if a depth contour is crossed, but can rarely be relied on to get a fix. Distance-finding stations associated with radio beacons and submarine diaphones (if the ship has receiving equipment) are other seldom-used piloting methods. Cross track position may also be determined by dead reckoning, either mentally or via chart plots. Accuracy of this method decreases rapidly with time since the last fix. Dead reckoning accuracy has been estimated to be 10 percent of the distance traveled if a plot is being maintained.

#### **B.2.3 Course Made Good Estimate**

Determining course made good can be used to update a dead reckoning track or to determine a compensation course to maintain the track. This can be determined by obtaining two fixes over a period of time or by estimating leeway accurately. Gyro error must be determined by azimuth or amplitude or, in the case of a pilot, it can be determined by consulting the crew or by observing a range whose bearing is known. Course made good in channels (Scenarios Three, Four, and Five) is determined from a time history of the cross track position and knowledge of the desired track line.

#### **B.2.4 Speed Made Good Estimate**

Speed estimate is important for developing an accurate dead reckoning track. The ship's ordered rpm can give a rough estimate of speed through the water; however, many ships have a speed log that can give a more reliable value. Actual speed made good requires a timed run of known distance; for example, time between fixes or ANs. This method is not always available. In its absence, wake and water flow at the hull (+4 knots) can be used as an estimate of relative velocity when passing stationary objects (ANs) close aboard.

#### **B.2.5 Wind Effects Estimate**

Without fix information keeping an accurate dead reckoning depends on the navigator's ability to determine leeway, which will indicate course and speed made good. To do this, the wind and current effects must be determined with an accuracy of 10 to 20 percent.

Wind direction relative to course and speed can be estimated by using meteorological instruments and reports or by guessing. Usually, the effect on the ship must be

observed via AN relative motion, considering the relative wind direction, draft of the ship (deeper draft means less wind effect), windage of the ship (sail area of the superstructure), or experience, if familiar with ship type.

The observed effects on course keeping, especially rudder bias required and wake effects, are useful in pilot waters where the distance between fixes is less than 1 or 2 miles. Wind effects on yaw are sensed and compensated for by the helmsman. Actual leeway effects are estimated by monitoring cross track position and speed made good via reference to ANs.

#### **B.2.6 Current Effects Estimate**

Pilots estimate current effects from memory or by consulting current charts for the harbor, knowing time of tide and time of channel transit. The observed current at buoys, objects, or anchored vessels can modify the original estimate since tabulated currents can vary with wind and barometric conditions.

The water surface (current lines, eddies, etc) can sometimes indicate the presence of a current; however, judgment of direction and velocity is difficult.

When pilot waters are bound by shoals, the set caused by tides is generally along track. Only estimated speed will be affected in these cases. When currents present a cross track set, the effects of current on cross track position are observed by the relative motion of the ANs about the ship. Ownship heading relative to the intended track line is another indication of current effects.

#### **B.2.7 Bank and Bottom Effects Estimate**

Bank and bottom effects are, by definition, problems only in Scenario Three, Four, or Five type navigation and involve hydrodynamic forces caused by the vessel's hull moving past a close-by bank or bottom. These forces affect the helm; however, the pilot will know this only if the helmsman is observant and experienced. These effects can be predicted if draft, trim, channel depth, and position relative to the bottom shoal are known. The pilot normally detects these effects by observing wake buildup effects; changes in ship response; or the carrying of helm bias by the helmsman. Roughly speaking, pilots often say that observing bank suction effects provides positional information. ANs marking shoal areas seem to be a safer source of this information.

#### **B.2.8 Ship Response to Helm Orders Estimate**

A pilot and helmsman must be able to accurately predict ships response to helm orders and its course keeping ability if they are to navigate safely in Scenario Three, Four, or Five type water.

Experience with similar ships provides the primary estimating technique. Monitoring maneuvers while underway is very important. Estimate of turn rate is required in turns along with an ability to see where the advance and transfer is carrying the ship so that corrective or pullout maneuvers can be made. ANs located at turns provide fixed reference points for observation of the ship's turn rate. Advance and transfer are gauged by observing AN relative motion to the outside or inside of the turn. Proper bearing rates of these ANs are learned through experience.

Estimating helm response and monitoring turns closely are not required in Scenarios One and Two.

#### **B.2.9 Response to Traffic Problems**

Traffic becomes a problem to the navigator when it obstructs aids or causes ownship to maneuver to avoid collision. The problem is greater in narrow channels in poor visibility because of the close proximity of opposite direction traffic.

Passing or being passed can distract from course keeping and, if the other vessel is close enough, can cause hydrodynamic perturbing forces. Traffic problems are likely in channel junctions, crossings, anchorages, etc. If the vessel's position is known relative to these places, the navigator can be alert to the need for collision avoidance. Passing traffic in narrow channels requires a more precise knowledge and control of cross track position because less lateral maneuvering room is available. ANs provide important indication of the absolute channel limits in Scenarios Three, Four and Five.

#### **B.2.10 Navigating the Ship through Decisions and Actions**

The navigator can initiate decisions and actions for a number of specific reasons. Six basic decision circumstances in all scenarios will cause the navigator to initiate a fix and to consider course, rudder angle, or rpm changes. These are:

- a. A planned turn point is being approached; wind gusts, current, other traffic, bank and bottom effects change or require changing the ship's course made good speed.
- b. The error in the dead reckoning has grown enough since the last fix to threaten ownship safety. A course change is required.
- c. The ANs about ownship align in such a manner that a fix taken at this time will have minimum error (e.g., AN abeam, equidistance between lighthouses, etc). A fix is executed and a maneuver considered.
- d. It is time for a normally scheduled fix. A fix is executed and a maneuver considered.
- e. The response to a maneuver, rudder order, or speed change is equal to or not equal to the response anticipated or required. Corrective actions are considered.
- f. The projected CPA to AN or shoal is unacceptable. A fix is executed and a new course selected.

Actions initiated as a function of various decisions included:

- a. Estimate present ship position, relative speed, and course; order appropriate courses, rudder angles, or speed changes. Such orders must necessarily compensate for the effects of set and drift observed from last fix or anticipated to affect the ship in the near future. Evasive maneuvers from shoals and ANs must provide the desired CPA.
- b. Use designated equipment or visual methods to obtain a fix.

- c. Vary fix frequency (either more or less often).
- d. Change or assign alternate levels of confidence to certain types of ANs and ship's equipment information.
- e. Take a fix based on information of only designated ANs.

These decision and action tasks occur in various combinations as situations warrant in various scenarios.

### B.3 MODIFYING NAVIGATIONAL TASKS FOR ENVIRONMENTAL EFFECTS

Such conditions as dawn, dusk, night, snow, fog, and rain alter the navigator's routine in all scenarios because of the difficulty in seeing non-lighted aids, prominent landmarks, topography, and traffic ships. Accurate and frequent position fixing, radar vigilance, and speed reduction are required to navigate safely.

Visibility reductions require similar actions from the navigator; however, additional whistle signals must be sounded and interpreted without being able to see the traffic ship or her running lights. Reducing speed further is important if reduced visibility is extreme. Determining the probable time of aid sighting while steaming in poor visibility ensures that the ship does not stand into danger if there is enough leeway to allow the vessel to pass outside the visibility circle of the aid. When the vessel's position is in doubt, the navigator must decide whether to proceed or to anchor and wait for better conditions.

The constraints of channel design require that the navigator decide which track line to favor, the turning method, and the time to turn. Buoy spacing can influence navigation and maneuvering since ANs must be avoided by the vessel. The pilot must negotiate transitions in channel boundaries and be alert to their effect on the vessel. A prudent mariner develops an avoidance maneuver as a contingency and often considers the character of the bottom when deciding where to leave the channel in an emergency where grounding is an expected consequence.

The following paragraphs describe the effects of specific conditions on navigation.

#### B.3.1 Effects of Darkness

The process of recognizing aids to navigation in darkness is one of interpreting light and acoustic characteristics and radar echo rather than identifying their number and structure. Of course, light and acoustic characteristics must be accurately identified. The navigator increases his dependency on radar since bearings and ranges can be taken on unseen and unlighted objects. DR navigation is unchanged except that the number of checks on dead reckoning are fewer; consequently, the estimated position error circle increases. Use of the methods for determining position in Scenarios One and Two, such as radar and LORAN fixes, is similar under nighttime conditions.

Channel ranges must be lighted for nighttime use. Use of landmarks is restricted to lighted objects which can be identified. Current effects remain unchanged by darkness; however, it is difficult or impossible to observe water surface effects and current at buoys, marks, and anchored vessels. Bank and bottom effects are not visible by wake effects. Ship response and turn rate can be more difficult to judge, but can be done by observing the compass and background lights. Other observed effects may not be visible.

Visual estimation of leeway is nearly impossible by observing wake, wind, and current effects. Leeway is estimated by comparing previous cross track positions.

### **B.3.2 Effects of Rain, Snow, and Fog**

The effects of reduced visibility from rain, snow, and fog are similar to the effects of darkness; however, there are some differences. Unlighted buoys not visible at night will be useful in daylight when they are within the visibility circle. Acoustic buoys may provide useful information such as location of channel entrances, junctions, shoals, and turn points. During rain, snow, or fog, lighted objects can be seen at ranges beyond the meteorological visibility at night (depending on luminous intensity) and to a lesser extent by day although the range in these conditions will rarely exceed 2 times the meteorological visibility at night and 1.3 times at day.

During reduced visibility, the navigator almost totally depends on radar; however, rain, snow, and combinations can reduce radar resolution. Visibility in snow can be less than the visual range in fog.

The traffic avoidance problem assumes equal weight with the maintenance of channel position. The requirement for speed reduction in poor visibility causes an increased current and wind-induced leeway between fixes. The ship tends to respond more slowly to helm and engine orders. More frequent fixes are taken in limited visibility (at-sea data bases). An accurate speed estimate can determine if the next aid was passed without observation. Increased decision-making time for navigation and for collision avoidance is an advantage of slower speed in reduced visibility. The severity of grounding is reduced, although the probability of grounding increases in bad visibility.

Buoy spacing in straight channels determines the time that the ship is steering "blind" in poor visibility. Turning in bad visibility, a critical problem dependent on buoy spacing, should not be attempted unless at least one buoy is visible at all times.

Sea state can cause difficulty in detecting buoys and small vessels both visually and with radar; however, this is rarely a problem for navigation in Scenarios Three, Four, and Five.

### **B.4 INFLUENCE OF AID TO NAVIGATION PLACEMENT ON THE NAVIGATION PROCESS**

Channel design can improve the safety of navigation in Scenario Three, Four, and Five type waters. For turns, close AN spacing is desired so that the boundaries of the curve are apparent in good and bad visibility. Types of channel buoy patterns include gated buoys (side-by-side at regular intervals); these are useful when determining cross-track position. Gated buoys must be distinguishable from one another to be useful for determining along track position. Gated buoys are easily identified on radar when traffic near the buoys is heavy. In interviews, pilots said that they prefer gated buoys and that this pattern allows easier and more accurate coursekeeping. Buoys arranged in an alternate or staggered patterns make the judgment of cross track position difficult, possibly hindering accurate coursekeeping.

When buoys are gated with a single line of buoys between gates, pilots tend to hug the non-staggered side; however, fewer aids are needed to mark a channel by this method. Opposite direction traffic in poor visibility can be dangerous since both ships prefer to

navigate on the side with the most aids. One additional method, used in Japan, is a fairway buoy system (aids down the channel center); however, this method does not adequately mark channel boundaries. Traffic lanes are close together in bad visibility; the buoys decrease the effective channel width since they must be avoided.

Accurately marking channel boundaries in turns rather than using any specific pattern of aids seems more important. Aids should maintain traffic in their proper lanes without causing ships to short cut out of the channel. The spacing of aids in turns should allow precise turning in poor visibility (i.e., less than 400 yards visibility) and ensure that at least one and preferably two aids are visible at all times. Buoys at turns must have distinguishing characteristics (acoustic and quick flashing) for identification to prevent early or late turning. Shoaling can occur on the inside radius of turns in channels with high tidal current velocities. Wider channels can separate traffic in poor visibility and allow greater error margins of cross track position. Bank suction effects are insignificant in wide channels; however, navigational aids on the opposite side may not be useful with lowering visibility.

In narrow channels the reverse of the above is true. Sloping at the channel edges can reduce total width forcing traffic closer to the center.

Appendix C  
AT-SEA DATA COLLECTION

CONTENTS

	<u>Page</u>
INTRODUCTION	C-2
Table C-1 Providence River - Narragansett Bay Actual Position Fixes	C-4
Figure C-1 Narragansett Bay	C-5
Table C-2 Providence River - Narragansett Bay Position Estimates	C-6
Table C-3 At-sea and Harbor Approach Fix Methods	C-7
Table C-4 Delaware Bay and River Actual Position Fixes	C-8
Figure C-2 Actual and Estimated Positions on Miah Maull Range	C-9
Figure C-3 Actual and Estimated Positions on Reedy Island Range	C-10
Figure C-4 Actual and Estimated Positions on Bellevue Range	C-11
Table C-5 Delaware Bay and River Position Estimates	C-12



## Appendix C

### AT-SEA DATA COLLECTION

#### INTRODUCTION

This data was obtained on a voyage from Providence, Rhode Island to Philadelphia, Pennsylvania on March 1 and 2, 1978. This report describes the data collection method used and presents the results.

1. Late in February, a trip on an American flag oil tanker was arranged. The ship left Providence, Rhode Island, at 2:00 p.m., navigated with a pilot down Narragansett Bay to below Newport, sailed at sea all night, picked up a Delaware pilot at 7:00 a.m. at the pilot area near Cape Henlopen and sailed with the pilot up the Delaware Bay and River to the Mantua Creek anchorage area off Miflin range, arriving at 1:30 p.m. The voyage provided 8-1/2 hours of pilotage time during slightly less than 24 hours sailing time.

2. During the trip down the bay in clear weather, the pilot relied on visual observations only. Floating ANs in the bay are numerous; the channel is narrow and twisting. Some fixed beacons are available. There are no Coast Guard installed ranges. One observer used the starboard wing pelorus to take crossed bearings on available charted objects in the upper channel and used the collision avoidance system bearing cursor to do the same on the lower bay. The second observer took photographs every half minute looking forward from the bridge from the same position and bearing, and recorded the pilot's orders/comments and behavior. The pilot was asked to estimate cross track position at several points. Initial subjective evaluation of the pilot identified a high reliance on floating aids taken as a group, coupled with use of informal ranges between land features and fixed lighthouses and between land features. Range estimates are only used when objects, such as buoys, were close aboard and directly abeam. Nearly all position finding is done as a result of bearing estimations.

3. TABLE C-1 gives a list of actual cross track positions of the ship relative to the port channel boundary in Narragansett Bay. These are also located on FIGURE C-1 which shows the chart of the bay. TABLE C-2 shows the differences in the pilot's estimated cross track position in the channel and the actual position of the ship along with the minimum distance to a hazard (such as shoaling to less than nominal draft) and the direction of the hazard. A ratio of position difference versus distance to hazard is also listed.

Departing Block Island Sound at dusk, the ship's officers navigated by radar ranges and bearings from Southeast light on Block Island and then from the light at Montauk Point. At sea, all fixes were by LORAN-A at about one and one-half hour intervals. Approaching Cape Henlopen, radar range and bearing fixes were taken on the shipping lane outer fairwater buoy to approach the lane and turn onto it. Thereafter, a radar range fix was made on each fairwater buoy as it came abeam. Fix methods and times are shown in TABLE C-3.

4. During the trip up the Delaware Bay (again in clear weather), the pilot relied on a combination of visual observations and radar observations. In the Delaware River the observations were all visual with heavy reliance on the Coast Guard installed ranges. Floating aids to navigation were substantially ignored by the pilot. Position finding in the bay area was from bearings to fixed light structures and from radar ranges to these structures when they were abeam.

5. During the trip up the river, one observer took bearings using the port wing pelorus on available charted objects and recorded times when ANs were abeam. These times were for later correlation of along track position to the pilot's orders and behavior. The second observer recorded the pilot's orders and behavior and took photographs at recorded times. Since the pilot relies on radar to transit the bay, he has developed a procedure for calibrating the radar accuracy at the head of the bay when outbound so as to better the nominal 1/10-mile accuracy which he ascribed to radar.

6. Frequent position fixes and pilot position estimates were recorded during transits of Miah Maull Range, Reedy Island Range, and Bellevue Range. This selection presented a variety of conditions from open bay on Miah Maull Range to closer in on Reedy Range to river channel on Bellevue Range. TABLE C-4 presents a list of actual cross track positions relative to the port channel boundary on these ranges. These positions are also shown in FIGURES C-2, C-3, and C-4. TABLE C-5 lists the difference in actual and pilot estimated positions on the ranges along with the distance and direction to the nearest hazard and the position difference/hazard distance ratio. The estimated positions are also shown in FIGURES C-2, C-3, and C-4.

7. This voyage demonstrated that at-sea data collection is important to understanding pilot behavior and to understanding information gained from pilot interviews and behavior at CAORF. It also demonstrated the feasibility of collecting data in pilotage waters including obtaining position fixes from means other than those used by the pilot. Both pilots were cooperative, open, and helpful. The data obtained will be useful in validating the AN model.

TABLE C-1. PROVIDENCE RIVER-NARRAGANSETT BAY  
ACTUAL POSITION FIXES

ACTUAL POSITION FIX NO.	DISTANCE TO PORT CHANNEL BOUNDARY (FT)	LOCATION
A1	300	BULLOCK POINT REACH
A2	375	"
A3	375	"
A4	180	RUMSTICK NECK REACH
A5	240	"
A6	270	"
A7	285	"
A8	180	"
A9	240	"
A10	330	"

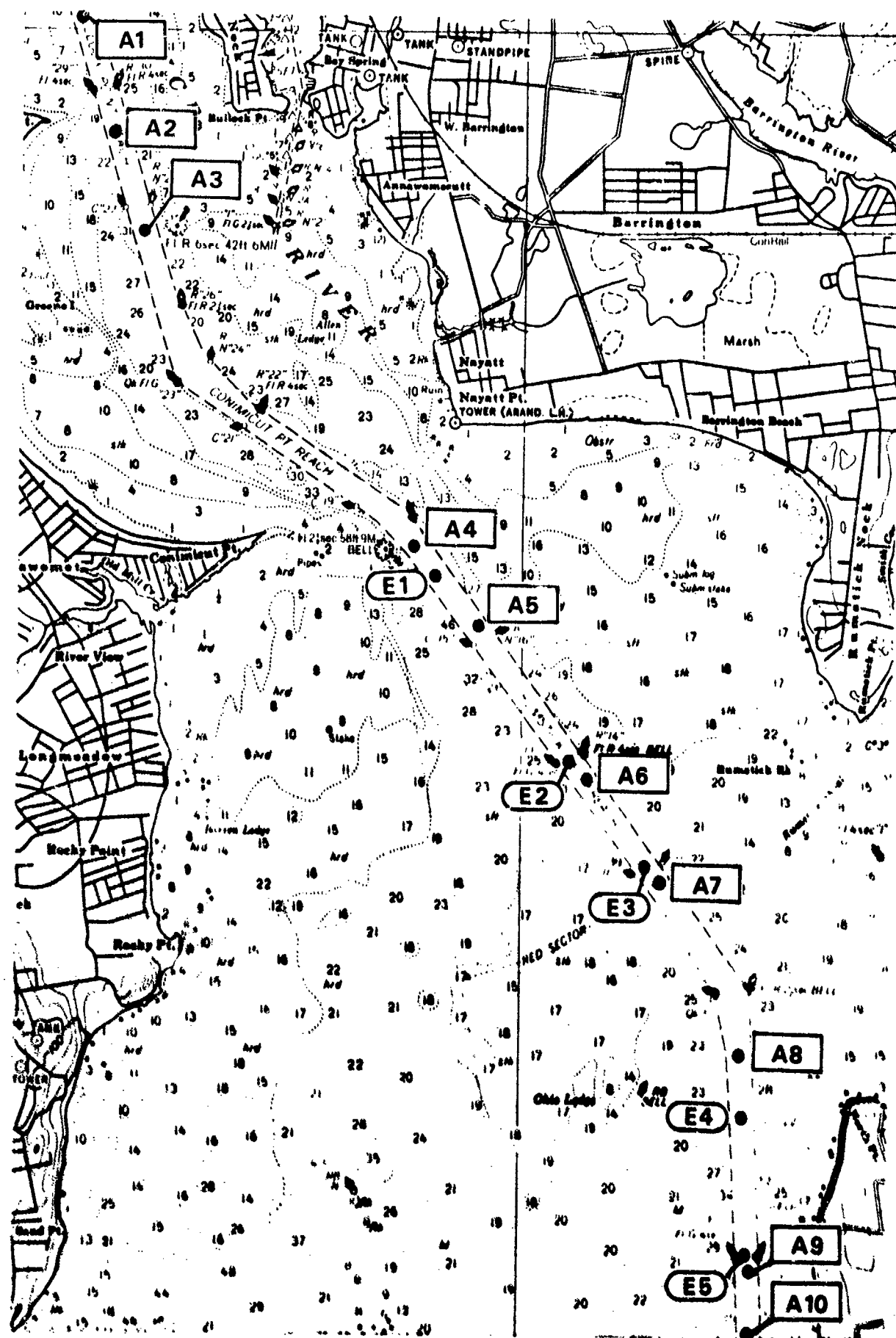


FIGURE C-1. NARRAGANSETT BAY

TABLE C-2. PROVIDENCE RIVER-NARRAGANSETT BAY POSITION ESTIMATES

ESTIMATED POSITION NUMBER	LOCATION	DIFFERENCE IN ACTUAL AND ESTIMATED POSITIONS (FEET)	ACTUAL POSITION TO PORT OR STBD OF ESTIMATED	MINIMUM DISTANCE TO HAZARD (FEET)	HAZARD TO PORT OR STBD	RATIO OF POSITION DIFFERENCE TO HAZARD DISTANCE
E1	RUMSTICK NECK REACH	120	PORT	480	PORT	0.25
E2	"	130	PORT	310	PORT	0.42
E3	"	110	PORT	340	STBD	0.32
E4	"	80	PORT	540	STBD	0.15
E5	"	70	PORT	360	STBD	0.19

TABLE C-3. AT-SEA AND HARBOR APPROACH FIX METHODS

TIME	NAVIGATION FIX TYPE	AN LOCATION/IDENTIFICATION
1713	RADAR B/R	BLOCK ISLAND LIGHT
1728	RADAR B/R	ABEAM BLOCK ISLAND LIGHT
1820	RADAR B/R	ABEAM MONTAUK POINT LIGHT
2020	LORAN-A	
2200	LORAN-A	
2330	LORAN-A	
0100	LORAN-A	
0200	LORAN-A	
0300	LORAN-A	
0340	LORAN-A	
0430	LORAN-A	
0458	RADAR B/R	R "F" SEA BUOY OF CAPE HENLOPEN TO FIVE FATHOM BANK TRAFFIC LANE
0535	RADAR B/R	ABEAM R "F" RANGE 0.45 NM
0605	RADAR B/R	ABEAM BW "FA" RANGE 0.5 NM
0637	RADAR B/R	ABEAM VW "FB" RANGE 0.5 NM
0700		AT PILOT AREA

TABLE C-4. DELAWARE BAY AND RIVER ACTUAL POSITION FIXES

ACTUAL POSITION FIX NO.	LOCATION	DISTANCE TO PORT CHANNEL BOUNDARY	CHANNEL WIDTH (FEET)
A 1	MAH MAULL RANGE	890	1000
A 2	"	870	1000
A 3	"	890	1000
A 4	"	940	1000
A 5	"	980	1000
A 6	"	950	1000
A 7	"	960	1000
A 8	"	900	1000
A 9	REEDY ISLAND RANGE	480	800
A10	"	490	800
A11	"	550	800
A12	"	550	800
A13	"	360	800
A14	BELLEVUE RANGE	453	800
A15	"	480	800
A16	"	507	800
A17	"	560	800

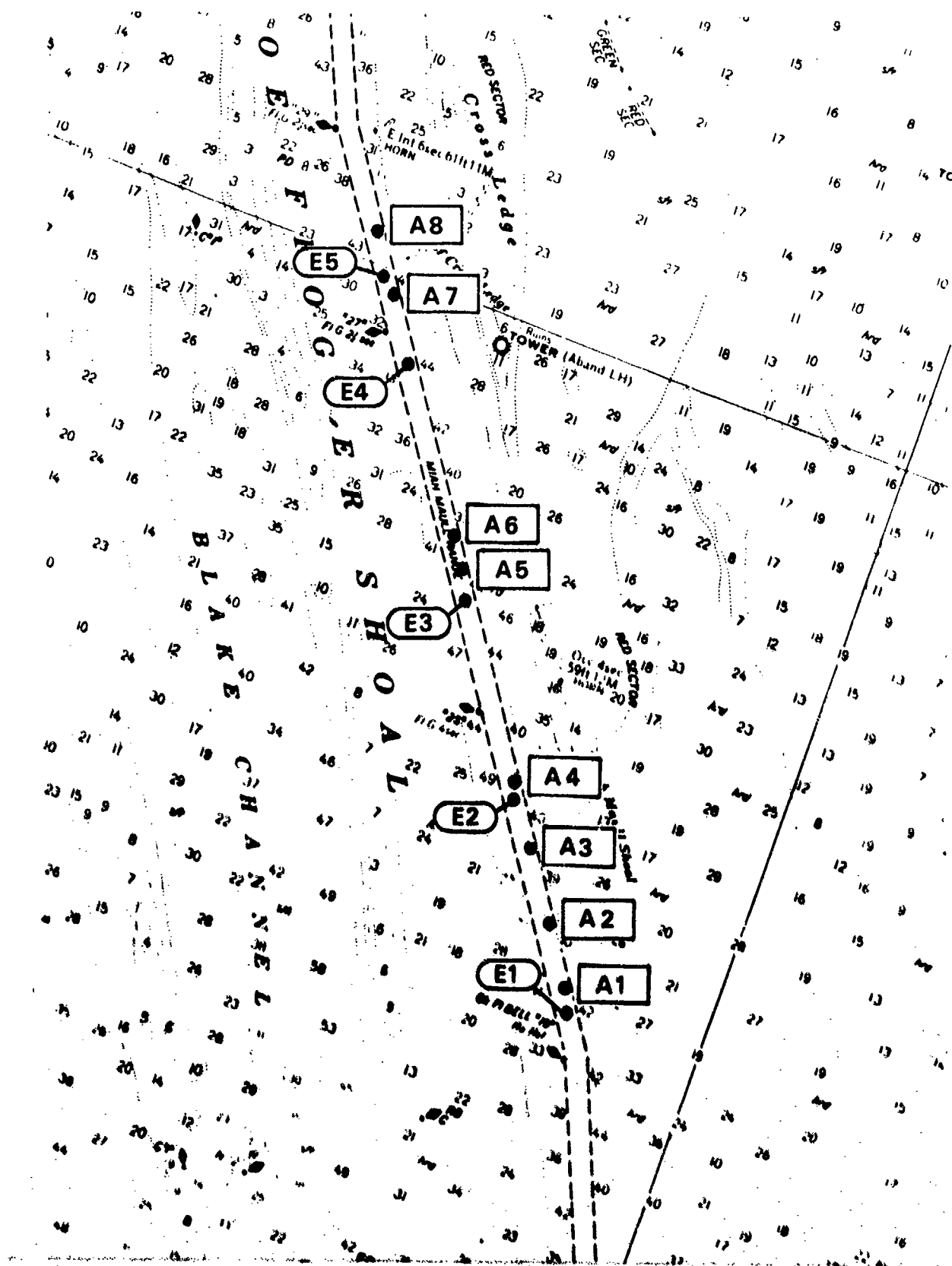


FIGURE C-2. ACTUAL AND ESTIMATED POSITIONS ON MIAH MAULL RANGE







TABLE C-5. DELAWARE BAY AND RIVER POSITION ESTIMATES

ESTIMATED POSITION NUMBER	LOCATION	DIFFERENCE IN ACTUAL AND ESTIMATED POSITIONS (FEET)	ACTUAL POSITION TO PORT OR STBD OF ESTIMATED	MINIMUM DISTANCE TO HAZARD (FEET)	HAZARD TO PORT OR STBD	RATIO OF HAZARD DISTANCE TO POSITION DIFFERENCE
E 1	MIAH MAULL RANGE	205	STBD	2800	PORT	0.07
E 2		480	STBD	2200	PORT	0.22
E 3		480	STBD	1850	PORT	0.24
E 4		160	STBD	1900	STBD	0.08
E 5		320	STBD	1550	PORT	0.18
E 6	REEDY ISLAND RANGE	10	PORT	410	PORT	0.025
E 7		165	STBD	590	PORT	0.28
E 8		180	STBD	610	PORT	0.29
E 9		180	STBD	1020	PORT	0.17
E 10		20	PORT	780	STBD	0.03
E 11	BELLEVUE RANGE	5	STBD	1370	STBD	0.004
E 12		15	STBD	420	PORT	0.035
E 13		20	PORT	240	STBD	0.083
E 14		20	STBD	240	STBD	0.083

Appendix D

SUGGESTED AN STUDY AREAS FOR NEW YORK HARBOR

<u>Section</u>	<u>Title</u>	<u>Page</u>
1	INTRODUCTION	D-3
2	BUOYAGE SYSTEM	D-3
3	HARBOR CONTROL	D-20
4	NEW ELECTRONIC AIDS TO NAVIGATION	D-22

## Appendix D

### SUGGESTED AN STUDY AREAS FOR NEW YORK HARBOR

NOTE: This appendix is a pilot's subjective viewpoint of the need for AN improvements in the Port of New York to establish target areas for preliminary application of the AN model.

#### Section 1

#### INTRODUCTION

The present system of navigational aids is the result of an evolutionary process and its scope is broad, ranging from the most elementary to highly sophisticated equipment, to match the capabilities of the vessels utilizing the system. Largely for economic reasons, the development has been somewhat haphazard, resulting in uneven coverage with concomitant room for improvement in both efficiency and safety.

With the objective of improving the efficiency and safety of navigation within New York Harbor, this report explores the design and placement of aids to navigation in the Harbor and its immediate environs. Section 2 enumerates 68 specific recommendations, ranked by three levels of priority, relating to the buoyage system. The recommendations are grouped by geographical area with reference to appropriate charts. Section 3 discusses harbor control and suggests specific areas where harbor control could be of benefit in relation to movements of ships and to anchorages. Section 4 briefly comments on new electronic aids to navigation.

## Section 2

### BUOYAGE SYSTEM

A recent reassessment of the aids to navigation in New York Harbor and vicinity has indicated a number of deficiencies in the present buoyage system, some of which should be corrected with immediacy, while others could be incorporated in a long-range plan of improvement. The present system, designed prior to the current level of tonnage and size of ship, is inadequate for present and projected needs.

The area most in need of improvement is that from Sandy Hook Channel through Raritan Bay Channel and Arthur Kill up to and including Tufts Point. The largest tankers and some containerships entering and leaving the Port of New York utilize this stretch of channel. It is also the probable route of any future LNG tankers. At the southern end of Tufts Point Bend is the site of the LNG dock at Rossville for servicing New York and New Jersey gas needs. The position of this dock poses a threat to the New York Metropolitan Area, as it is under the bow of every south-bound tanker and containership as they turn 72° at Tufts Point. (A relocation of the dock to the New Jersey side of the channel on the inside of the turn would virtually eliminate the possibility of a passing ship colliding with an LNG ship alongside the dock and should be considered in the interest of safety.) Regardless of the position of this dock, however, the channel is in need of improvement, both in the form of widening and in assistance from improved navigational aids. A local junkyard has effectively reduced the Tufts Point Bend improved channel width of 800 feet to approximately 500 feet, and this situation should be corrected. It is also recommended that an existing buoy in this area (Buoy 20) be lighted to clearly define the outside edge of the turn.

Another area of difficult navigation is the East River, which presents the most severe ship handling conditions in New York Harbor due to strong tidal currents caused by the difference in times for turning of the tide in the two bodies of water (Long Island Sound and the Harbor Upper Bay) at either end of the river. Although an experienced pilot is the best defense against accidents in this area, several improvements in navigational aids can be made.

These and other recommendations are included in the Table of Recommended Changes to Aids to Navigation in New York Harbor, which follows. Each recommendation is ranked as Priority 1, 2 or 3. Included in Priority 1 are those recommendations that are considered to be essential to the safety of shipping in the harbor area. Priority 2 recommendations are next in order, but still of substantial import, followed by Priority 3 recommendations, which are in the "nice-to-have" category. The Table of Recommended Changes includes six general areas: Sandy Hook to Tufts Point, the Raritan River, Tremley Point Reach to Shooters Island, Constable (Con) Hook to north of Newark Bay North Reach, Ambrose Channel, and East River to Sands Point.

For long-range planning, the AN model should study improvements in channel markings and in channel layout for safety and efficiency.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
SANDY HOOK TO TUFTS POINT				
1	12327/12324: Sandy Hook Channel	Add radar reflectors to buoys 1, 2, 8, 9, 14, 15a, and the 1 Qk Fl G buoy at the en- trance to Terminal Channel. (See also No. 3 and 4.)	2	For ease in locating these buoys on radar.
2	12327/12324: Sandy Hook Channel	Make buoy 16 lighted.	1	The buoy marks a definite shoal in an area with strong tidal set, but is difficult to locate at night.
3	12327/12324: Sandy Hook Channel	Make buoys 1, 9, 15a and 17 beacons.	2	Severe weather can move buoys 1 through 9. Heavy winter ice can move the buoys from the junction of Chapel Hill Channel through 12 and 13 and deposit them in the vicinity of buoys 9 and 10 or on False Hook. (Note: Some years ago buoys 1, 9, and 17 were re- placed by beacons, but subsequently destroy- ed by collisions.)
4	12327/12324: Sandy Hook Channel	Continually reposition buoy (beacon) 15a to the north as Sandy Hook moves. Insert necessary notices in Notice to Mariners.	2	To keep the buoy (beacon) marker current with the changing land shape.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
5	12327/12330/ 12324: Raritan Bay Channel	Add a lighted buoy 5 opposite buoy 6 and a lighted buoy 13 opposite buoy 14.	1	To improve visual estimates of latitudinal position in the channel; particularly important for safety when laden ships are passing each other. Also, to aid in determining position when the buoys on one side are moved for dredging; this would obviate the need for checking for bank suction to determine position.
6	12327/12330/ 12324/12331: Raritan Bay Channel	Add a set of range lights at either end of the 7-1/2 mi Raritan Bay East and West Reaches.	2	For ease in navigation.
7	12327/12331: Red Bank Reach	Add a lighted buoy (or make an exist- ing buoy lighted) between buoys 36 and 46, preferably between beacon 42 and buoy 36 opposite buoy 39.	3	Red Bank Reach lacks a lighted buoy.
8	12327/12331: Ward Point Bend (East)	Replace Mun 54 with a lighted buoy.	2	To prevent outbound ships from turning short because of difficulty in visualizing N54's position at night.



TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
9	12327/12331: Ward Point Bend (West) between bea- con 58 and old Totten- ville ferry racks on Staten Is- land side.	Reserve buoy 60 for a position 0.2 mi above beacon 58 should Perth Amboy Anchorage ever require one. Add buoy 62 in line with the east side of the Rar- itan River Cutoff. Add buoy 66 directly off the old Tottenville racks. Add buoy 64 half way between buoys 62 and 66.	1	To clearly mark the channel limits on the Staten Island side. This section of channel is a 1.1-mile inside curve that periodically shoals. Ships that venture close to the Staten Island side have been known to lose control and be repelled by the bank across the channel.
10	12327/12331/ 12332: Great Beds	Substantially increase candle power of Great Beds Light.	1	Because of its frequency of use and criti- cality to these uses as listed below: a. As a heading light for outbound ships in Ward Point Bend West. (Note: in con- junction with buoy 62 proposed in rec- ommendation 9 above, it would be inval- uable in describing the shoal north of that buoy.) b. In line with Great Beds Reach beacon 4 for a $78^{\circ}/258^{\circ}$ course in Ward Point Bend East. c. In line with a dock in South Amboy at latitude $40^{\circ} 29' 30''$ N and longitude $74^{\circ}$ $16' 35''$ N (which could also use a light) as a centerline and best course to steer to prepare for the number of course changes in this area.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
11	12327/12331/ 12332: Ward Point Sec- ondary Channel	Dredge the shoal marked by the Secondary Channel buoy 5 by about 150 ft. Remark this area as follows: a. Move buoy 5 to 400' 120' from its present position. b. Place Fl G 1 immed- iately south of gong 1. c. Equip gong 2 with a flashing white or quick flashing red light. d. Make Can 3 lighted.	2	To reduce the severity of the turn into Great Beds Reach. The relocating of buoys would mark the southern part of the channel by a line from buoy 5 to buoy 1.
12	12327/12331: Port Socony Reach	Move buoy 6 about 350 ft north. Move buoy 8 about 150 ft south and make it lighted.	2	To accurately mark the southern and northern Port Socony Channel entrances. The present locations of the buoys promote shortcutting the edges of the Channel entrances.
13	12327/12331: Port Socony Reach	Position a lighted buoy 9 in the turn opposite beacon 10.	2	To mark the southern corner of the short stretch of 800-ft wide channel in order that it can be more fully utilized as a passing zone, particularly for ships entering and exiting the Hess Port Reading Oil Terminal.
14	12327/12331: Port Reading Reach	Make Can 15 off Port Reading a lighted buoy.	3	For better identification.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
15	12327/12331: Tufts Point Bend	Make buoy 20 lighted.	1	To clearly indicate the outside edge of the turn. (See introductory text.)
16	12332/12331: Raritan River	RARITAN RIVER  Make buoys 5, 5A, 4B, 6, and 7 lighted. (Buoy 4B should have a white light to avert confusion with buoy 4C.)	3	For ease in navigation.
17	12332/12331: Raritan River	Add a light on the Carbarundum Plant at 40° 30' 38.5"N lat- tude and 74° 15' 28"W longitude in line with the center pin of the CRR Bridge.	3	To serve as a heading light for the 126° South Amboy Reach.
18	12332/12331: Raritan River	Add a north light on the stack at latitude 40° 30' 56" and long- itude 74° 17' 30". Add a south light on the second railroad trestle at latitude 40° 29' 33" and long- itude 74° 17'.	3	These would provide heading lights for Sandy Point Reach.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
19	12322/12331: Raritan River (above Thomas Edison and Garden State bridges)	Make buoy 11 lighted. Add a lighted buoy on the Perth Amboy side opposite buoy 11. Make Can. 1 of the Titanium Reach lighted. Add a heading light at approximately 40° 30' 40" N latitude and 74° 18' 34" W longitude.	3	Currently only barge traffic uses this stretch of River, however, it is poorly marked, even for the low level traffic. (Note: The upper Raritan River has not been assessed, but should be evaluated if ships use the Titanium or Arsenal facili- ties.)
20	12322/12331: Raritan River	Make all range and heading lights single red lights, beamed to heading, and give them distinctive character- istics, such as Mo(R).	3	Normally, ranges and heading lights that are red stand out best against background lights. The distinctive characteristics would enhance this quality.
TREMLEY POINT REACH TO SHOOTERS ISLAND				
21	12327/12333: Tremley Point Reach	Make buoys 32 and 36 lighted.	3	For ease in navigation.
22	12327/12333: Arthur Kill, North	Add buoy north of EXXON Dock basin to complement buoy 17.	3	To assist in positioning the ship's bow while turning.
23	12327/12333: Elizabeth Reach and Shooters Is. Reach	Change the Elizabethport range light from a single light to a set of range lights.	2	This range light marks a distance of 1.1 miles. For westbound traffic, the single light does not mark the channel well enough.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
24	12327/12333: North of Shooters Island Reach	Make Nun 20 lighted.	3	For ease in navigation.
		CONSTABLE HOOK TO BEYOND NEWARK BAY NORTH REACH		
	Note: This area is called the container capital of the world and these are the narrowest channels container ships will pass through in the Port of New York.			
25	12327/12333: Constable Hook Approach	Add buoy 25 Qk Fl W at latitude 40° 38' 59.5"N and longitude 74° 03' 57"W.	2	With buoy 2, this would properly mark Baxter's Ledge. In addition to the difficult navigation always encountered in transiting from a large fairway (NY upper Bay) to a more restricted one (even though this channel is 1400 ft wide, heading and range are 113° rather than 110°), most phases of both the ebb and flood tides set onto Baxter's Ledge.
26	12327/12333: Constable Hook Approach	Add a lighted buoy 1 at latitude 40° 38' 57"N and longitude 74° 04' 39.5"W.	2	To mark the southern side of Constable Hook Approach.
27	12327/12333: Constable Hook Approach	Renumber Can 1 as Can 3.	2	This need not be a lighted buoy as it is close to one. Ships can steer in an easterly direction from this buoy toward buoy 2 and clear the Can.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
28	12327/12333: Constable Hook Reach	Renumber buoy 3 as 5. Renumber buoy 4 as buoy 6.	2	In conjunction with recommendation 26.
29	12327/12333: Constable Hook/Bergen Point East Reaches	Add 1 lighted buoy 7 at latitude 40° 30' 46.5" N and longitude 74° 06' 27"N.	3	For ease in navigation.
30	12327/12333: Bergen Point Reaches	Make Bums 8 and 12 lighted buoys. Properly position the red light on the north side of the Bayonne Bridge. Eliminate Num 10.	2	For ease in navigation.
31	12327/12333: Bergen Point West Reach	Make Can 11 lighted.	1	This would greatly improve navigation, both turning into and out of Newark Bay, in conjunction with the red lights under the Bayonne Bridge positioned over the south side of the channel.
32	12327/12333: Newark Bay South Reach	Make Can 3A just below the Jersey Central RR Bridge lighted.	2	Since the widening of the channel off Texaco Bayonne, ships tend to unwittingly approach this buoy too closely.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
33	12327/12333: Newark Bay Reach	Add light at latitude 40° 39' 16.5"N and longitude 74° 08' 34" W at heading of 190° (on the Newark Bay Bridge).	2	To provide a heading light for southbound traffic from Upper Newark Bay, Port Newark, and Port Elizabeth.
34	12327/12333: Newark Bay	Make all buoys off Port Elizabeth marking its middle ground shoal lighted (i.e., Cans 7 and 1, Nuns 7 and 1) and also make all buoys off Port Newark marking its middle ground shoal lighted (i.e., Cans 13A and 3, Nuns 10, 8, 6, 4* and 2*).	1	Nuns 4 and 2 (with asterisks) are the most important. Since ships often pass in the Port Elizabeth Channel, and since the shoal does not line up with the north side of Port Elizabeth, unlighted buoys make a night pass- ing difficult. (At least one tug has been overtumed here by a ship bringing it too close to the tank with a resulting loss of life.)
35	12327/12333: Port Newark Channel	Make Num buoys 6, 12, 16 and 18 lighted.	3	Buoy 18 nearly lines up with the north side of Port Newark Channel, but beacon 19 does not.
36	12327/12337: Newark Bay North Reach	Add a light on the New Jersey Turnpike Bridge heading 199° at lati- tude 40° 40' 48"N and longitude 74° 07' 27.5"W.	3	As a heading light for ease in navigation.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
37	12337: Newark Bay and Hacken- sack River	Make Can 21 and Nun 24 of Newark Bay lighted. Make Nuns 2, 6, and 10 of the Hackensack River lighted. Add a lighted buoy oppo- site buoy 10 in the Hackensack. Make Can 11 lighted.	3	For ease in navigation.
38	12327: Ambrose Channel	ADD RADAR REFLECTORS to buoys at the begin- ning and end of the channel (i.e., buoys 1A, 2A, and 18. Buoy 18 already has one.) Add radar reflectors on all turning buoys 9, 10, 13, and 14) in- stead of on Cans and Nuns.	3	For ease in locating these buoys on radar.
39	12327/12349: Ambrose Channel, West Bank	Add light on Sevin- burne Island in line with the axis of the second leg of Ambrose Channel.	3	To serve as a heading light for the second leg of the channel.



TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
40	12327/12349: Ambrose Channel, Gravesend Bay	Add ranges and/or buoys in the Grave- send Bay area when dredging is completed.	3	To aid in anchoring at least three large, deep draft ships.
41	12327/12349/ 12334: Ambrose Channel, The Narrows	Make the lights under all bridges, particu- larly those under the the Verrazano Narrows Bridge, navigating the aids, indicating the sides of channels and mid channel. Add to all navigational charts.	3	For ease in navigation.
42	12327/12334: Ambrose Channel, Robbins Reef	Add a light in line with Robbins Reef.	3	As a heading light to give the outside edge of Staten Island anchorage.
43	12327/12334: Ambrose Channel, Upper Bay	Place the grids for the Upper Bay anchorages on the Upper Bay charts.	3	As an aid to navigation.
44	12327/12334: Ambrose Channel Upper Bay	Make Can 1 and the red/ black Nun, lighted buoys in the Caven Point and Claremont Terminal Chan- nels.	3	Although seldom used, this channel has a considerable cross set.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
45	12327/12334/ 12335: Ambrose Channel, Hudson River	Add lighted buoy 33 at latitude 40° 41' 50"N and longitude 74° 02' 01"W.	2	To describe the shoal off Ellis Island.
46	12341: Hudson River	Eliminate Weehawken- Edge-Water Channel.	2	This channel does not follow the normal course of the river, and consequently silts up. It is unmarked, difficult to find, ex- pensive to maintain, and infrequently used.
47	12150: Hudson River	Add a lighted buoy above George Wash- ington Bridge lati- tude 40° 51' 15"N and longitude 73° 56' 46.5"W.	2	To mark Dumping Ground Shoal.
48	12150: Hudson River	Possibly add a radar reflector to buoy 2 above Spuytín Dryvel.	3	For ease in navigation.
49	12150: Hudson River	Possibly buoy the 30- ft curve from Edge- water to Yonkers.	3	This is probably unnecessary because it would interfere with towing and be expensive to maintain, while not being warranted by the safety records for shipping in the area.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
		EAST RIVER TO SANDS POINT		
50	12335: East River at House Flats Poor	Establish a range light for nighttime navigation by lighting the prominent, tall stack between 35th and 36th streets.	2	The range light is required for marking a relatively narrow passageway between threatening rocks for a deeply laden ship. The rocks cannot be buoyed because smaller draft ships pass them, and because buoys could present a hazard to tows.
51	12339: East River off Lawrence Point	Make buoy 15 lighted, and if possible, move it slightly to the west.	1	To properly mark the western extremity of the rock. Eastbound traffic, when passing westbound traffic, often comes surprisingly close to this buoy.
52	12339: East River off North Brothers Island	Add a lighted buoy at latitude $40^{\circ} 48' 04''$ N and longitude $73^{\circ} 54' 06''$ W.	3	In conjunction with buoy 15, this would describe the line of the shoals from Lawrence Point to North Brothers Island. It would also aid westbound traffic and that turning south off North Brothers Island.
53	12339: East River off North Brothers Island	Make buoy 5 lighted.	3	Eastbound traffic swings overly wide at night to avoid the unlighted buoy.
54	12339: East River, west of Borretto Point	Mark the 27-ft rock at latitude $40^{\circ} 48' 09.5''$ N and longitude $73^{\circ} 53' 20''$ W.	2	This rock lies near the course of a westbound ship docking at the Texaco Dock on the Gypsum Dock at Oak Point.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
55	12339: East River, east of Borretto Point	Mark the 9-ft spot at latitude $40^{\circ} 48' 01''$ N longitude $75^{\circ} 53' 20.5''$ W.	2	This area can lie close to the course of a westbound ship experiencing traffic.
56	12339: Hudson River north of Rikers Island	Mark the rock at latitude $40^{\circ} 47' 53''$ N and longitude $73^{\circ} 52' 55''$ W. Add a light on Rikers Island in line with the channel light on the Whitestone Bridge.	3	For ease in navigation. The light would serve as a heading light.
57	12339: East River, off College Point	Move buoy 3 to latitude $40^{\circ} 47' 47.5''$ N and longitude $73^{\circ} 51' 42''$ W.	2	In conjunction with the other buoys in this area, this would better mark the area and shoal, while permitting ships to turn around off College Point, if necessary (as during a tugboat strike).
58	12339: East River, Hunts Point	Mark the eastern extremity of the 30-ft curve running from Hunts Point at latitude $40^{\circ} 48' 01''$ N and longitude $73^{\circ} 53' 23''$ W.	3	For ease in navigation.
59	12339: East River, College Point	Make the bell buoy of College Point lighted.	3	For ease in navigation.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
60	12339: East River, Col- lege Point	Mark the extremity of the 30-ft curve running east from College Point light at latitude 40° 48' 05"W and longitude 73° 50' 16"W.	3	For ease in navigation.
61	12366: East River, off Whitestone Point	Add a buoy at latitude 40° 40' 09"N and long- itude 73° 49' 07"W.	2	To mark the extremity of the shoal for ships making a turn.
62	12366: East River at Throggs Neck	Mark the sewer outlet on Throggs Neck at the eastern end of Anchor- age 6.	3	To indicate anchorage to the north and good water to the south.
63	12344: East River, off Willeys Point	Make Nun 2 lighted.	3	For ease in navigation.
64	12366: East River, off East Chester Bay	Make buoy 4 lighted.	2	To indicate the location of the East Chester Bay shoal for westbound ships when meeting traffic.
65	12366: East River, off Stepping Stones	Possibly add a buoy 1200 ft to the north- west.	3	This would be convenient for large ships, but might be unwelcome by tows and small cargo ships.

TABLE OF RECOMMENDED CHANGES TO AIDS TO NAVIGATION IN NEW YORK HARBOR (CONT'D)

NO.	CHART REFERENCE	RECOMMENDED CHANGE	PRIORITY	COMMENTS/RATIONALE
66	12366: East River, off Hart Island	Increase the intensity of Hart Island Light. Use the City electric system, backed by bat- tery power.	2	Ships come too close to this point because of difficulty in locating the lights.
67	12366: East River, off Prospect Point	Make bell 23 lighted.	1	Because of difficulty in locating this buoy (and the shoal it marks), ships come too close to Execution Rocks.
68	12366: East River, off Hart Island	Have the stacks at lat- itude 40° 51' 04"N and longitude 73° 46' 0.5" W lighted.	2	To serve as a heading light for ships on a 50° - 230° course passing Execution. (This would also be an important aid if ice moves buoys 46 and 25.)

### Section 3

#### HARBOR CONTROL

Without a formal harbor control in New York, only two major accidents occurred in a recent ten-year period, the first attributable to lack of VHF communications before the popularity of portable radios, and the second to a mechanical steering system breakdown not backed by a completely parallel system. However, with the goal of increasing the efficiency of cargo movement without detriment to safety, harbor control of ship movement, if properly conceived and implemented, could to some extent resolve traffic flow problems in the harbor. The dual responsibility of safety and efficiency requires that traffic control guidelines be implemented with judgments predicated upon both experience and hard data. To be effective, it also requires a flexible organization.

In some European ports, working pilots rotate periodically into the control system, bringing to it invaluable current ship handling experience on a twenty-four hour basis. The extent of involvement of the harbor control organization can vary considerably, as evidenced by the European port organizations which offer a good cross-sample for study. In Rotterdam, for example, the harbor control completely controls the movement of some large ships, the spacing between intermediate-size ships, and the bulk flow of barge traffic.

The concept of harbor control is controversial. Harbor control, if improperly implemented, could become a negative rather than a positive force as, for example, if it should be concerned only with safety subsequent to maritime difficulties as in the Sea Witch-Esso Brussels collision.

In any harbor control system, two broad areas of control exist: primarily, movement of ships, and secondarily, anchorages. A brief tabulation of suggested areas of involvement for the proposed New York Harbor Control pertaining to each of these follows.

#### MOVEMENT OF SHIPS:

1. A schedule of arrivals, departures, and transportings to enable traffic to utilize the port's capacity to the fullest.
2. Identification of name, type, location, agent, destination, and needs of the larger sea-going ships for scheduling purposes and for information to other navigators.
3. Scheduling of priority regarding ship's position within a group of vessels on a tidal situation bound to destinations in the same general area.
4. Designation by radar or other means of safety margins.
5. Scheduling or assisting the meeting and passing of major water movements (e.g., sea-going ships, large tows, large contingents of small vessels in areas such as Tufts Point, Tremley Point, Bergen Point, and Hell Gate) by use of radar monitors about the harbor.

6. Issuance of warnings about dangerous situations and advice on handling of those situations.
7. A depository for problems encountered or experienced.
8. An immediate source of assistance in case of need or unusual circumstances.
9. A cataloging of harbor problems for future solution.
10. An information center for weather update and for variations from the published tide tables.
11. Navigational advice to a piloted ship with a particular problem, either directly from Harbor Control or through directed inter-pilot contact.

#### ANCHORAGES:

1. Scheduling of the lightering of tankers at the crowded New York anchorages, so that all have an anchorage when needed or when convenient.
2. Reservation of anchorage so that once a ship (especially a large tanker) is committed up the channel to an anchorage, there will be an adequate one still remaining when she arrives.
3. Shifting of anchored ships awaiting berths from anchorages only when necessary (as for possible tidal problems).
4. Maintenance and periodic issuance of an accurate grid presentation of ships anchored on both the flood and ebb tides to interested parties.



## Section 4

### NEW ELECTRONIC AIDS TO NAVIGATION

Certain electronic aids not fully utilized today and those future aids currently under experimentation, when coupled with the irreplaceable experience, knowledge, and expertise of a good pilot, may afford more safe and efficient navigation systems in the near future. A brief discussion of the foremost among these, with suggestions for improvement and utilization, follows.

1. LORAN in U. S. waters and Decca in European waters provide the navigator with similar information. The equipment is, however, generally located in the chart room and therefore not handy for certain types of navigation. On deep vessels (VLCC) traveling through a large fairway to a berth (e.g., Rhode Island, Block Island, Long Island Sounds to the Northville Dock) where a narrow proposed track has been side scanned for obstructions, a LORAN or Decca monitor attached to a chart table next to the radar in the wheelhouse could be invaluable in maintaining that track.
2. The radio navigation aid system for entering Antifer and the "Brown Box" at Rotterdam seem to hold much promise for the future. At present at Antifer and Rotterdam, the ship's equipment for the system is carried aboard the ship by the pilot. Since pilot transfers are made whenever possible, and in winds up to force 8 by helicopter, there seems to be little problem in handling this equipment. In New York, however, it is doubtful how much equipment, if any, a pilot would be willing to hand carry from ship to ship. Should this type of equipment be installed aboard ship, and the ship and the shoreside Harbor Control have monitors, then precise information regarding a ship's lateral channel position and rate of changes in that position would be available. Should such equipment become dependable and trouble-free in conjunction with excellent radar presentations, it could permit safe piloting under more severe conditions (e.g., ice having removed or shifted buoys).
3. Controlled Radial Steering-Kockums Automation A.B. Sweden (See International Symposium, Grenoble 77). This is a computer-controlled device that determines the timing and extent of rudder application for a particular ship in a particular turn. The system utilizes the true motion radar presentation to evaluate the success of the maneuver. Bottom bank suction, wind, and currents cause some difficulty with the system. It should be recognized that maintaining a position in a channel is comparatively easy in a straight stretch as opposed to a turn, and that turns in excess of  $45^\circ$  become excessively difficult; further, a channel with straight stretches and turns is better than one with a long, slow arc. Ward Point Bend is an example of a difficult channel in which to maintain position. The turn, which is some  $107^\circ$  in magnitude, is not made with a continuous arc, which is the preferred method, but is severe at the beginning and end, and moderate in the middle. It necessitates a great amount of helm to get the vessel swinging, then a reduction or counter-rudder to slow the swing, followed by additional helm to create a quick swing again, and finally counter-rudder to steady up on a course.
4. The transponder system (CAORF Symposium 77, J. Johnson) allows a vessel to identify another ship similarly equipped and receive information regarding her

style, course, speed, draft, etc, and also question through code her intentions. With the subsequent identification, it permits ship-to-ship communication via VHF regarding those intentions.

5. Doppler Log should be fitted on all large ships (VLCCs) that have no other method of determining final rate of approach to a dock. In the channel it can give longitudinal speed over the ground as well as actual course made good. This information in relation to ship's heading and speed would give the navigator tidal set.
6. Side scanners used to check for obstruction clearance in a fairway could possibly give channel position.
7. A computer linked to a collision avoidance system with the radar in the north up mode could possibly determine lateral position and set within the channel and also speed over the ground. A monitor could then give a readout.
8. Maersk Line supposedly has a system which permits a ship to follow a predetermined track without other input. (Further information was unavailable as of this writing).
9. Finally, the USCG has been experimenting with LORAN-C in the St. Mary's River. This holds promise as a universal aid not tied to specific ship's equipment.

Appendix E  
SIMULATOR RESEARCH FACILITIES REVIEW

<u>Section</u>	<u>Title</u>	<u>Page</u>
E.1	FRANCE	E-2
	E.1.1 Grenoble (Port Revel)	E-2
	E.1.2 LMT Simulator	E-2
E.2	UNITED KINGDOM	E-2
	E.2.1 Decca Simulators	E-2
	E.2.2 Hull Nautical College	E-3
	E.2.3 Marconi Onboard System	E-4
	E.2.4 University of Wales	E-4
	E.2.5 Solartron Systems	E-5
	E.2.6 Department of Trade and Industry, CGI System	E-5
E.3	NETHERLANDS	E-6
	E.3.1 Netherlands Ship Model Basin	E-6
E.4	GERMANY	E-6
E.5	DENMARK	E-7
E.6	SWEDEN	E-7
E.7	JAPAN	E-8
	E.7.1 Osaka -- SIR151	E-8
	E.7.2 University of Hiroshima	E-8
	E.7.3 IHI	E-8
E.8	UNITED STATES	E-9
	E.8.1 CAORF	E-9
	E.8.2 Marine Safety International	E-10

## Appendix E

### SIMULATOR RESEARCH FACILITIES REVIEW

Numerous research facilities for merchant vessel simulation exist worldwide. Collectively, these facilities represent a wide variety of simulation techniques, level of fidelity, and costs of operation. Representative systems devoted to ship handling and navigation are briefly summarized below. We have on file a fairly complete reference to each of the operational systems listed.

#### E.1 FRANCE

##### E.1.1 Grenoble (Port Revel)

This facility was one of the first to address the issue of VLCC ship handling. Although abandoned by Exxon, it is still in use as a training facility. The major problem of visual perception differences and lack of transfer from scale models to the real world is the important lesson learned from this simulation attempt. Other problems include distance estimation and the reaction time in 5X real world. The facility has simulated, from 1/25th scale tankers including 255,000-, 192,000-, 38,000-dwt and one 37,400-dwt LNG carrier. For reasons of visual differences and the lack of environmental control, the facility is judged as having a low potential application to the AN problem.

##### E.1.2 LMT Simulator

This facility, currently under development, exists on a prototype and has a very high fidelity visual image. Hybrid CGI and TU technique are applied in a narrow visual field. Full color capability is present. The facility is judged as having a high potential to AN studies as a function of its visual resolution. Draw-backs include the fact that it will not be operational for at least a year and little or no research backup equipments are planned.

#### E.2 UNITED KINGDOM

##### E.2.1 Decca Simulators

A facility exists at Decca for research and equipment demonstration purposes. The facility is a night vision system, basic in design with limited equations of motion for a general ship class. Following this general design, the U.K. Department of Industry and the Ship & Marine Technology Board awarded a contract to Decca and National Physics Laboratories to fabricate a more elaborate system for U.K. training.

The simulator consists of a model wheelhouse with a bridge control console including wheel and autopilot, engine throttle, anticollision radar, ship's telephone, radio communications, warning annunciators, and a chart table. Mounted above the

bridge window are indicators including heading repeater, log, rate of turn indicator, engine revolutions, and clock. Engine and propeller noises and vibration are generated, varying correctly with engine revolutions. The bridge window has a 100-degree arc showing the bow of the ship, lights of navigation, marks and lights of other ships. Up to 16 lights, white and colored, can be shown at one time and they will move with correct perspective, as own ship moves and as other ships' aspects change, and they are all correctly correlated with the echoes on the radar display.

The simulator provides anticollision, navigation, pilotage, and ship handling exercises with the vessel responding to wheel and throttle to represent specific vessels ranging in size from a coastal fishery craft to a 500,000-dwt tanker. Tides and currents can be reproduced in terms of varying depths of water under the keel.

The simulator can be programmed for real or artificial exercise areas, which can be changed in a few minutes by inserting different magnetic tape cassettes. Each exercise is automatically recorded on a track plot for subsequent analysis, together with recordings of rev/min, ship speed, rudder angle, rate of turn, drift angle, and heading. Applicability to AN is judged as low.

### E.2.2 Hull Nautical College

This simulator driven by two PDP-11/40's is for storage of complete port approaches, land fall areas, and fishing grounds. The radar simulation includes land masses and clutter. This simulator was heralded as the "world's first fully Integrated Marine Navigational Simulator" in 1974. The system was developed by Marconi.

All features of navigational importance, such as buoys, coastlines and hills, which are used for position fixing by radar, are part of the digital coastline system. The analog generator provides land "fill-in" effects. Sea clutter is generated and the targets increase in size with decreasing range. Up to 48 radar targets can be generated for an exercise; of these, 40 are preprogrammed and 8 are instructor controlled.

The system has three control bridges. "Own Ship 1" is a fully equipped ship's bridge. The layout of this bridge is similar to many modern ships and this part of the simulator complex is used for advanced training of deep-sea navigators. Own Ship 1 is equipped with an independently controlled Mk 21 Decca Navigator. The decimeters detail the correct readouts for the position of ownship in the exercise area unless the instructor wishes to insert errors such as lane slip. A Marconi Marine Lodestar II direction finder is also installed and three simulated df stations are provided within the playing area.

Own Ship 2 was designed to give formal instructions in decision making and on the correct operation and interpretation of modern fish detection equipments and the handling of fishing gear. A full set of fishing electronics is provided and all the hazards of snagged trawls and gear damage can be reproduced.

The Own Ship 3 simulator is used for training pilots in maneuvering and collision avoidance procedures and for improving their skills in operating procedures. There is also a "Shore Surveillance" cubicle which has been designed to give pilots training in traffic control from the shore. Applicability is judged as low.

### E.2.3 Marconi Onboard System

Marconi Radar Systems, Ltd. has produced a portable simulated timebase and echo generator (TEG) which is designed to reproduce on an existing radar display the phenomena of surface craft, aircraft, sea clutter, noise, and a number of other special effects. The device can be interfaced with most shipborne radars. In the basic system, seven "other" ships can be shown in addition to ownship. Additionally, eight targets can be shown, together with simulated land effects.

The complete STEG equipment consists of a compact unit housing a small computer, an intermediate unit whose size depends upon the radar fitted, and a small, hand-held keyboard, with a flexible lead.

Several exercises are possible with the basic equipment. The sequence of events consists of: set up the radar simulation, set up the target simulation, impose the effects, and begin the exercise. The instructor is able to freeze the action or change and reset at will. It is possible to use the radar tactically during the time that the situation is taking place. Real targets can be incorporated into an exercise if desired.

The targets shown are both realistic in strength as well as movement. Two normalized curves are used to calculate the fading characteristics of a target so the effect of small targets and distant objects can be realistically reproduced. Side lobe effects are simulated at short range and it is possible to introduce blind arcs similar to those found on the ship itself. A fixed turning rate is used for changing the heading of either the target or own ship so that relative motion is changed at a realistic rate. A number of turning rates applicable to a variety of ship sizes available. Both sea clutter and thermal noise can be generated so that the scene on the PPI is at all times realistic. The equipment is capable of generating a variety of pulse lengths and beam widths. Applicability to AN is judged as low.

### E.2.4 University of Wales

The university has installed one of Solartron's SY2080 Marine Simulators.

A control room at the Institute houses the coastline generator and computer cabinet, target generator, plotter, monitor display, telephones to ownships, and the main VHF control console. The console has three cubicles representing ownship bridges fitted with radar display, VHF transceiver, telephone, and chart table.

The components found in the control room allow the operator to carry out procedures for the selection of coastline, positions of own ship, and four targets. Thirty-two targets may be given characteristics, which vary from small craft to supertankers and from hovercraft to aircraft. Tide or current may be applied to affect the movement of vessels.

The monitor display provides a 13-in. diameter stabilized relative motion picture which is switched to view from one of the own ship positions. Plotting is carried out automatically at selected time intervals by means of a Bryan's XYT plotter. The speed of each ownship is shown on its respective repeater indicator.

Each of the three ownship units is fitted with an AEI Escort radar. Two have 16-in. diameter displays and true motion facilities; one has a 13-in. relative motion

only display. All have reflector plotters as standard equipment. The control module provides the observer with the usual controls available to officers keeping a bridge watch/engine control via a telegraph-type selector and helm control, either manual or automatic. A compass repeater indicates the course steered. Speed is indicated in knots in two switched ranges: 0 to 30 or 0 to 90.

The operator can select the type of vessel that own ship represents, its maneuverability, and its size. Initial course and speed may be preset.

The VHF R/T simulator provides two-channel, bridge-to-bridge communication, or ship-to-shore, as required; one channel is utilized as the international emergency and calling channel (designated 13); the other is used as a work channel (such as 6 or 14).

The console situated in the control room enables propagation conditions on each channel to be selected, and the state of each ownship equipment to be set. Thus, receiver or transmitter failure may be simulated, on one or both channels, and prevailing transmission/reception conditions varied on either channel. The operator is in contact with all ownships and may act as the watchkeeper on any of the targets, or as a shore controller or station operator. Both channels are continuously monitored and, in this respect, exercises may be recorded as an aid to later analysis. Applicability to AN is judged as low.

#### E.2.5 Solartron Systems

Solartron has a wide variety of simulators installed or on order; including Vancouver Institute, Liverpool Polytechnic, MARAD (New Orleans), Greece, and Bulgaria.

The system generally consists of two computers (a special purpose computer for conversion of Cartesian coordinates to range and bearing, and a general purpose mini-computer), one 12-in. and three 16-in. anticollision radar displays (all Decca solid state), and hardware backup. All hardware except the general purpose computer and Decca displays are manufactured by Solartron, and the program is being written by their in-house software team.

The system incorporates Solartron's Interactive Keyboard/Terminal (IKAT), which allows the operator to create exercises without the need to acquire any computer programming expertise. The system is programmable for a variable number of ownships (8) and targets (32). Applicability to AN is judged as low.

#### E.2.6 Department of Trade & Industry, CGI System

This system is under development at this time and will be placed at one of the British schools (Southampton or Liverpool). Preliminary data indicate that the system may find a medium degree of applicability to AN studies.

### E.3 NETHERLANDS

#### E.3.1 Netherlands Ship Model Basin

The wheelhouse of the simulator at this facility contains a complete display and control panel, a radar simulator (Raytheon 16 inch), and a chart room. Inside illumination comes partly from some spotlights outside the wheelhouse illuminating the ceiling to simulate reflectance from the water surface.

The wheelhouse is placed inside a large cylindrical screen with a diameter of 20 m and a height of 10 m. The design of the wheelhouse and the position of the windows ensure that the upper or lower ends of the screen cannot be seen. The screen consists of a wooden frame, plated with plasterboard and painted with highly reflecting wall paint.

The projection system is located above the wheelhouse. High-pressure xenon lamps provide two point light sources with an effective area of 1 mm. Both lights are located in the middle of the cylindrical screen. The bottom light projects sky, landmarks (such as coastlines and harbor entrances), and part of the sea. The upper light adds brightness to the sky and projects part of the sea that cannot be covered by the bottom light. Sky and sea are produced by sceneries painted on cylinders that turn around the light sources. The landmarks are projections of a model mounted on an arm. The model rotates and moves along the arm; the arm rotates around the light source. A picture of the front part of the ship is projected onto the screen by two wide-angle slide projectors. The point light-source projector is shielded for that area.

The computer system is a hybrid, allowing speed and accuracy tradeoffs.

Recording takes place on a multichannel pen recorder for direct monitoring; punched-tape recordings are produced on command. Usually rudder motions, rate of turn, course, trajectory, forward speed, and some integrated error scores are recorded. Instrument inspection behaviors can be checked from a closed circuit television. If the shipmaster remains seated, psychophysiological measures such as heart rate, GSR, EEG, or eye movements can be recorded. Applicability to AN is judged as medium.

### E.4 GERMANY

Germany in its recent revamping of its "System of Nautical Education" selected a radar simulator (capable of handling four ownship and six targets) which has been in use since 1973 and a shiphandling simulator, which has been in use since 1974. The latter system, developed by VFW-Fokker, is installed at the German Academy of Nautical Science in Bremen. The VFW-Fokker simulator, in the standard version, can be programmed to represent a supertanker of 200,000 dwt, a container ship of 66,000 dwt and bow thruster, and a standard freighter of 15,000 dwt.

Visual and instrumentation simulation can represent open sea, coastal areas, port entrances, and canals.

Simulated maneuvers can include starting and stopping engines, emergency stop, collision avoidance (including visual display of approach vessels), turning



circle, Williamson turn, man overboard maneuver, search courses, homing, berthing, anchoring, and mooring.

Navigation and communication subsystem simulation includes terrestrial landmark displays as well as LORAN, Decca, echo sounder, radar, and radio direction finder inputs. A digital computer is programmed for wind, current, and water depth parameters.

The operator's actions can be monitored from an observer's position. The observer can insert instrument and machinery failures, course changes of approaching vessels, wind shifts, etc. Basic programming information was obtained from recorded behavioral data of real vessels rather than from water tank models. Experienced ship captains participated in the development program. Applicability to AN is judged as medium.

#### E.5 DENMARK

The Danish Ministry of Merchant Marine for the Fano Navigation School installed Redifon type C.8012 in the spring of 1973. It provides facilities to observe subjects in marine radar operations, blind pilotage, and radar navigation. The simulation includes two radar equipped ships, six target craft, and coastline generation. (Similar systems exist at navigation schools in Copenhagen and Svendborg.)

The simulator incorporates a DEC PDP-8/M digital computer with 12K of core store and five Decca marine solid-state radar displays, including anticollision true motion, and relative motion units. An exercise recorder provides a continuous record of all movements of craft throughout an exercise.

Each cubicle is fitted with a ship control system and a radar display, and during the course of an exercise the position, speed, or course of any target craft can be altered. Alternatively, he can preprogram an exercise, thereby allowing him to give more individual instruction to the students. Applicability to AN is judged as low.

#### E.6 SWEDEN

A facility has been in service since 1973 at SSPA, Goteborg. The SSPA Steering and Maneuvering Simulator is driven by a hybrid computer facility, consisting of two large analog computers and one digital computer with associated interface, and display and recording systems; in addition, two smaller analog computers are employed for high speed continuous solutions of the ship dynamics problems.

The bridge mockup includes a forward maneuvering area with consoles along the front bulkhead, a separate steering console, and a navigation area aft of this console, a standard chart table, and radio-navigation equipment displays. The width of the bridge is approximately 15 ft. Seven TV screens in the front bulkhead windows are used for the presentation of the real world image.

The visual display is based on a closed-circuit TV system scanning the electronically generated real world image. Through the windows navigation

beacons such as lighthouses, buoys, leading lines, and simple topographic formations are seen in true angular perspective against a background of sea and sky in dark and light grey. (Simple shapes of moving ships may also be shown.) In the centerline ownship's bow is displayed as viewed from helmsman's position at the steering console. As ownship moves, the forward view is progressively changed.

When maneuvering close to mooring buoys or berthing piers, the real world image may be complemented with a bird's-eye view on a separate CRT screen in the navigation console at the forward steering position. A simplified radar display is produced on an oscilloscope stand on the port side of the consoles, or on the CRT screen just mentioned.

The navigation console is centrally located. To port is a communications console. The steering console is in the normal steering position for manual steering with a true view of the outside world, within +40 degrees from the centerline. Applicability to AN is judged as limited to hydrodynamic variables, since the visual fidelity is low.

## **E.7 JAPAN**

Japan has a wide variety of systems under development and operational, including the Tokyo University of Mercantile Marine, Osaka University Department of Naval Architecture (SR151), the University of Hiroshima (since 1970), IHI (Tokyo (since 1975), and JRC system (since 1966).

### **E.7.1 Osaka -- SR151**

This system is a TV model, servo positioned and displayed on a circular screen. The system is similar to other model board approaches.

### **E.7.2 University of Hiroshima**

This system is a rear screen projection system with an electronically generated image. The screen is flat, not cylindrical, and similar to the IHI system described below.

### **E.7.3 IHI**

The Ishikawajima-Harima Heavy Industries Co., Ltd. simulator uses a visual display system which clearly projects in color on a large screen (7 meters by 3 meters) the views of the sea, sky, horizon, islands, buoys, and other vessels which change with the movement of the vessel it is designed to simulate. The simulator has a simulated bridge of a 200,000-dwt class tanker, with equipment, including a steering and a main engine control level and various instruments, arranged as a navigation bridge to accurately represent changes in a ship's motion. The system is capable of a wide range of preprogrammed ship's characteristics including VLCCs and ULCCs. The field of vision is 0.5 mile to 8 miles. Applicability to AN for all Japanese simulators is judged as low due to their potential problems with availability and working arrangements.

## E.8 UNITED STATES

The U.S. has several facilities which are available for study or eventual use by the Coast Guard. A brief discussion of the major systems follows.

### E.8.1 CAORF

This facility was recently accepted by the Maritime Administration from its vendor Sperry Systems Management. The major components include: simulator bridge, control station, central data processor, image generator and display, radar communications, and a main computer program.

A key feature that sets this system apart from the majority of others discussed is its flexibility, resulting from its having been designed for research purposes, rather than for training as most of the other facilities were. A second major feature is the computer-generated image generation.

The image generator generates a color pictorial representation of the view through the wheelhouse windows over an angle of +120 degrees to -120 degrees in relative bearing and +10 to -14 degrees in elevation. This scene includes shoreline, topographic features, major features such as bridges and buildings; all significant navigation marks; other ships, both moving and anchored; docking areas; and those portions of own ship's structure visible from the wheelhouse. The view of large objects, landfalls, etc corresponds to a spherical earth. The generated scene corresponds to an observer's eye height, selectable within the range of 25 to 100 feet above sea level. The nominal operational environment (gaming area) is 100 by 50 nautical miles. It is possible to display up to six moving ships in the visual scene at the same time in addition to own ship. The visual scene changes, in real time, in accurate response to own and other ship maneuvering motions, except that visual effects of wave-induced motion are not displayed; the sea is shown without waves, and the sky is devoid of clouds and celestial bodies.

The image generator is capable of representing various levels of scene illumination. Haze or fog can be simulated. It is also possible to model any geographic locality as the gaming area when required through reprogramming.

The radar signal generator generates real-time video signals coordinated with the visual display for driving the radar PPI displays and an idealized radar display. The PPI displays simulate the radars on the simulator bridge, whereas the idealized radar display simulates an idealized radar without target shadowing, clutter, attenuation with range, receiver noise, etc.

The gaming area contains features normally found in the open sea, harbors, and docking areas. The area includes navigation aids (buoys, lighthouses, etc), the shoreline, other topographic features, and moving and anchored ships. These features and up to 40 moving target ships can be displayed.

The communications subsystem simulates the communications link to the external world. It provides the simulated wheelhouse with contemporary merchant ship communications capabilities. Communications equipment includes a sound-powered telephone; ship intercom system; single-sideband HF radio; VHF radio; and own and other ships' whistles. The control station is the external terminal of the simulated wheelhouse communication elements.

The computer program is the software utilized by the CDP to drive the simulator bridge. It performs computations required to simulate ownship motions in real time in response to steering and propulsion commands originating on the simulator bridge, or alternatively, to remote steering and propulsion from the control station. In addition the program accepts and processes simulated steering, propulsion, and other malfunctions introduced at the control station. It generates signal data to simulate ownship control responses, to drive bridge displays and status indicators, and realistically reflect malfunction inputs.

The program controls the motion of up to 40 target ships in real time, either along preprogrammed tracks or in response to speed and course commands originating at the control station.

The program generates outputs required by the radar signal generator and the image generator and display system to develop radar PPI and situation displays and the visual scene.

The computer program also allows recording of simulation run data to permit resetting the simulation to selectable past points in time, either for reinitializing the run or for playback of the run as it actually occurred. It also permits the collection of simulation run data for post-run analysis of the problems.

The applicability of this system is very high as proven in Phase I of this program. In addition, new projectors being installed will additionally increase the visual image quality substantially over the currently acceptable condition.

#### E.8.2 Marine Safety International

MSI has entered the field of commercial training for the crews of Texaco and El Paso Natural Gas. The system has a full-scale bridge with the equipment found on a 250,000-dwt tanker. The visual scene is created by moving a TV probe over an accurate model board of selected ports (Wales, Delaware River, etc). Targets are presented on radar as well as by a fixed track method. The visual system uses a double reflection method to reduce the distance and light loss problem and uses eidophor projectors. The system is driven by a digital computer in real time and has the flexibility of programming any class of ship. Current simulations are for a 250,000-dwt tanker and 135,000-cubic meter LNG carrier. The system represents a logical combination of the state of the art at a reasonable cost for full scale simulator training. The system is judged not compatible with research program requirements.

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